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Tracing Beach Sand Movement with Irradiated Quartz

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Abstract—The mechanics of transportation of sand under the influence of wave action was studied using artificially induced radioactivity. A sample of naturally occurring quartz sand is taken from the area of study, subjected to slow neutron irradiation, and then reintroduced into the area. The movement of the quartz is traced by sampling the sediment on the bottom and assaying for phosphorus-32, which is the principal radio isotope formed from the slow neutron irradiation of natural quartz sands.

In a field experiment, 860 g of irradiated quartz sand was reintroduced as a point source on the sea floor off Scripps Beach. The experiment showed that the dispersal of sand by wave action was more rapid than expected, and that the movement of this small amount of sand could be followed for about 7 to 24 hr. The irradiated sand was released on the bottom by divers and samples were obtained on a grid at the time intervals of ¼, 1, 3½, 7½, and 24 hr, and several days later. At the point of introduction the water was 10 ft deep and the surface waves were about 1½ ft high. The waves caused the sand to spread in an elliptical pattern with an elongate onshore-offshore axis. The sampling indicated that the 860 g of irradiated fine sand had been dispersed over an area of approximately three-quarters of a square mile in 24 hr. The sensitivity of detection for this experiment was approximately 1 grain of sand in 100,000.

Introduction—Until recently there has been no satisfactory means of tagging grains of sand so that their movement could be studied in the beach and nearshore zone. The advent of readily available high flux neutron sources for activating sand samples has given impetus to studies involving the tracing of sediment movements. The purpose of this investigation was to perfect a field technique using low levels of radioactivity in sands, and to apply this technique in studying the rate of dispersion of sand under wave action near shore.

Previous work with radio isotopes as tracers of sand has principally been confined to the use of foreign particles such as ground glass, which are added to the sand under study. Also, previous investigators have employed levels of activity too high for use along California beaches [*Hours* and others, 1955; *Inose* and *Shiraishi*, 1956; *Putman* and *Smith*, 1956; *Arlman* and others, 1957; *Davidsson*, 1958]. Foreign particles are not usually suitable for beach sand tracers because their hydraulic behavior may be different from that of the natural sands. To be satisfactory, the natural tracer of sand movements should be: (1) not a health hazard, (2) of the same size, density, and shape as one of the major components under study, (3) easily and rapidly distinguishable from the sand mass, (4) inexpensive and available in relatively large amounts, and (5) able to retain its distinguishing properties over times comparable to the times of the fluid processes. Thus, the problem was to seek out a tracer that would fulfill these requirements and to develop field techniques that could be used in the difficult conditions encountered near the surf zone.

Since quartz is one of the dominant components of most sands, a method of tagging it was highly desirable. The technique by which *Goldberg* and *Inman* [1955] utilized phosphorus-32, which is formed when normally-occurring phosphorus in quartz sand is subjected to slow neutron irradiation, satisfactorily fulfills the requirements for a tracer. In addition phosphorus-32 does not constitute a health hazard when used in this manner near populated beaches. Phosphorus is a low level beta emitter which occurs as a minor impurity in the order of hundreds of parts per million in quartz. The phosphorus mineral involved may be an orthophosphate, possibly berlinite ($AlPO_4$), which is isostructural with quartz. Since each radioactive quartz particle can be detected on photosensitive film, sensi-

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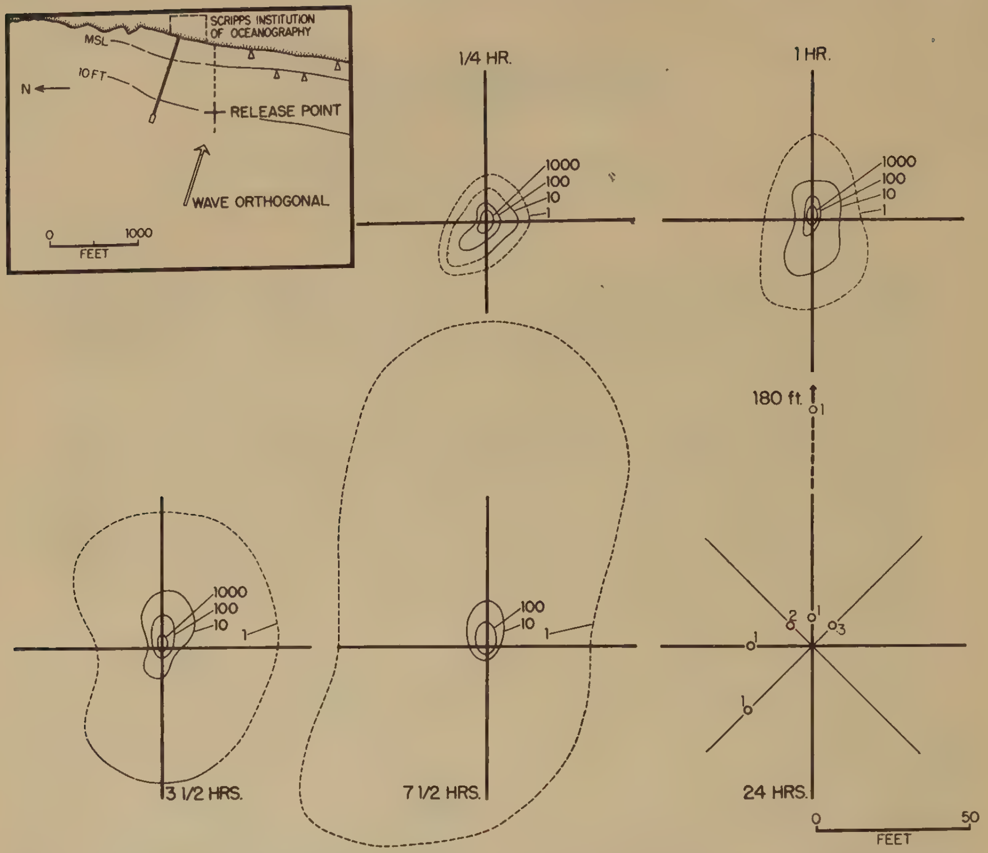

Fig. 1—Distribution of irradiated sand particles with time. The contours are lines of equal concentration of surface particles, and their value is expressed in number of irradiated particles per 0.1 sq ft (100 cm^2). At 24 hr only six offshore samples gave returns, which are shown as individual points. The four positive beach counts for the 24-hr sampling are plotted in the inset. Orientation of grid is shown in the inset.

tivity of the assay is limited only by size of sample and size of film. Single irradiated quartz particles can easily be detected when mixed with about one million inactive particles. Phosphorus-32 has a half-life of 14.6 days, and irradiated quartz particles could be detected for several months.

To carry out the study, a natural sample of sand was obtained from the environment to be studied. The quartz grains were concentrated by partial removal of other constituents, the resulting concentrate was irradiated, and it was then reintroduced into the natural environment by swimmers equipped with self-contained underwater breathing apparatus (SCUBA). After reintroduction of the irradiated sand on the bottom, the area was periodically sampled to determine the rate of dispersion of irradiated particles. Two types of samples were taken: (1) the surface layer of sand, obtained by impressing a grease-coated 3 × 5-in card on the bottom, and (2) cores, obtained by forcing small plastic vials into the bottom. The activity of the surface sample was assayed by laying the sample card on photosensitive film and, after exposure and development, counting the exposed spots. The cores were solidified with plastic resin and sectioned before assaying.

Since it was desirable to use an area that was convenient to reach from the laboratory and one in which good wave and tidal data could be obtained, the sandy beach and shelf immediately

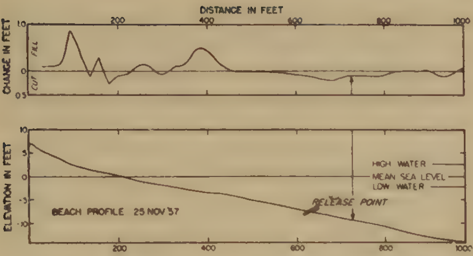

Fig. 2—Changes in sand level along the beach profile during first 40 hr of the experiment. Erosion (cut) occurred in the vicinity of the release point; deposition (fill) occurred on the beach. Location of profile shown in Figure 1.

adjacent to the Scripps Institution of Oceanography was chosen as the field locality in which to carry out the experiments (Fig. 1). The shelf is flat and is uniformly covered with fine and very fine sand. The irradiated sand was released on the bottom by swimmers at a point where the water depth was about 10 ft. During the observations the surface waves were about 1½ ft high and the wave period was about 14 sec (Table 1).

Laboratory method—The natural sand collected from the experiment site was composed of about 68 pct quartz, 20 pct feldspar, 10 pct heavy minerals, and 2 pct shell fragments [*Inman*, 1953]. Thus it was necessary to process the sample in order to concentrate the quartz. The sample was first washed and treated with dilute HCl to remove the calcareous shell material, then dried and sieved, and the smallest size group discarded because it contained little quartz. The magnetic minerals were removed with an electromagnetic separator, after which the sample was placed in hot *aqua regia* for 24 hours. The sample resulting from the above treatment was nearly 98 pct quartz and feldspars and compared closely in size distribution with the natural sand of the experimental area (Fig. 3).

The concentrate of 860 g of sand, prepared as outlined above, was sent for irradiation to the Union Carbide Nuclear Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee. There it was placed in the atomic pile and subjested to slow neutron irradiation with a nominal flux of 10^{12} neutrons/cm^2 sec for 14 days. Following irradiation and prior to shipping, the sample was cooled for seven days to allow for the removal of the induced Na and K activities in the feldspar impurities. After receipt at the laboratory, the irradiated sand measured approximately 16 mr/hr at the surface of the container. Beta absorption measurements were taken, and

Table 1—*Wave and tide data*

Time after release	Depth of water at release point	Wave[a] height	Wave[a] period
hr	ft	ft	sec
½	11.3	1.3	15.0
1	11.6	1.2	14.3
2½	11.9 (highest water)		
3½	11.7	1.1	13.9
7½	8.6	1.4	13.3
10	7.7 (lowest water)		
24	11.0	1.9	13.0

[a] Height and period of the highest one-third of the waves measured during a 20-min interval. The maximum wave measured during each interval was about 1.6 times greater.

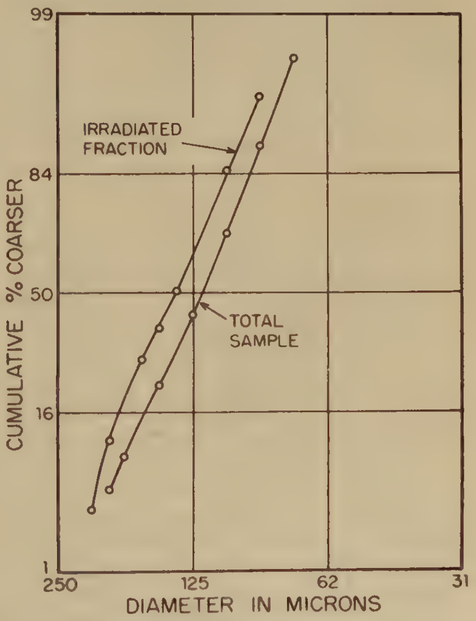

Fig. 3—Particle size distribution curves for the total sample of natural sand and the concentrate of quartz sand which was irradiated and reintroduced into the area of investigation.

(3)

they showed the presence of the phosphorus 1.7 Mev beta particle. Measurement on half-life indicated that the short life contaminants did not contribute significantly to the over-all activity.

The sample was dyed an intense blue (Night Blue, National Aniline No. 598) before introduction to the experiment site. Coloring the tracer permitted the first stages of the dispersion to be followed visually.

Counting technique—To determine the quantity of irradiated sand in each sample collected, the 3 × 5-in sampling cards, covered with sand grains, were brought from the field and wrapped face to face with No-Screen X-ray film in a light-tight package. The film was exposed 24 hr in this manner, then developed and fixed. The irradiated sand grains showed themselves quite easily as black spots on the resulting transparent film negative.

The small cores collected in the field were brought into the laboratory and solidified by the injection of plastic resin. They were then sectioned lengthwise and laid upon photosensitive film for the required exposure period. The result was similar to that obtained from the surface samples, and counts could easily be made of the irradiated grains.

Sensitivity—Tests were conducted on a portion of the irradiated sample to determine the sensitivity of the photosensitive film in recording individual radioactive sand grains and to determine the most desirable exposure time to use at various decay times. It was found that thin wrapping paper placed between the irradiated particles and the X-ray film absorbed most of the radiation, but that "Saran Wrap", an extremely thin sheeting of vinylidene chloride made by Dow Chemical Company, allowed the radiation to penetrate and register on the film. Saran Wrap was used to protect the film from the greased sand sample in all experiments. Thirty days after irradiation an exposure time of 4 hr gave weak returns from the control sample, while 12 hr was adequate to give strong signatures from all irradiated grains. Four months after irradiation, high contrast could still be obtained from all particles in the control sample with an exposure time of 16 hr. Exposure times longer than 48 hr were excessive and resulted in clouding the film, thereby obscuring particle counts.

Prior to the release of irradiated sand, 32 samples of sand were collected from the area of investigation to determine the natural background activity of the region. These were processed in the usual way with an exposure time of 24 hr. Although each sample contained about 100,000 particles of natural sand, no

TABLE 2—*Distribution of irradiated sand particles* (2.44 × 10^{8} *irradiated particles were released*)[b]

Time after release	Number of surface samples	Number of cores	Number of particles accounted for by sampling			Area of[c] distribution,
			Surface	Subsurface	Total	
hr ½	32	0	3.25 × 10^{6}	1.19 × 10^{8}	1.22 × 10^{8}	sq ft 0.73 × 10^{3}
1	37	9	0.93 × 10^{6}	1.19 × 10^{8}	1.19 × 10^{8}	1.5 × 10^{3}
3½	42	5	0.19 × 10^{6}	0.77 × 10^{8}	0.79 × 10^{8}	5.3 × 10^{3}
7½	42	11	0.24 × 10^{6}	0.31 × 10^{8}	0.31 × 10^{8}	17.2 × 10^{3}
24	74	5	scattered returns approximately			24 × 10^{6}[d]
7 to 23 days	84	9	no positive returns			indeterminate

[b] 860 g of very fine sand were released.

[c] Area over which concentration of irradiated particles per sq ft was 10 or more. This is a surface concentration of 1 in 10^{5} particles.

[d] Assuming total number of irradiated particles to be dispersed so that concentration per sq ft is 10 or less as indicated by sampling.

(4)

positive exposures were found. Supporting this assumption of no detectable background activity were the results of the actual sampling itself. The last irradiated grains were detected from the sampling at 24 hr. Subsequent to this, 84 surface samples were taken in the area, none of which showed the presence of irradiation.

Field procedure—The field work was carried out by SCUBA-equipped swimmers operating from a small boat. Concurrent with the sand sampling a pressure-type wave meter was used to record wave conditions, and current measurements were taken using a captive drogue. Principal operations were concluded in 24 hr, although background sampling was continued for 23 days. A total of 311 surface samples and 39 cores was collected and processed (Table 2).

The irradiated sand was carried to the center of the grid in a plastic bottle by a swimmer. There the plastic bottle was opened and the irradiated sand poured out onto the bottom, covering an area of about 3 sq ft. Samples were taken at predetermined positions on the grid at ¼, 1, 3½, 7½, and 24 hr, (Fig. 1, Table 2). Also, background samples were obtained throughout the area 7 and 23 days after the release, but they did not show the presence of irradiated particles.

A permanent sampling grid was established prior to the actual experiment. It consisted of a series of reference stakes driven into the bottom at 10-ft intervals along eight ranges radiating from the release point. The major onshore-offshore range extended through the breaker zone onto the beach (Fig. 1). The beach profile and its changes are shown in Fig. 2.

The principal sampling was performed with 3 × 5-in paraffin-coated paper cards, covered on one side with Varcon #4-1645 Water Pump Grease. Each sample was taken by pressing a sampling card onto the bottom so that the surface layer of sand grains adhered to the coating of grease. In addition, subsurface samples were obtained by forcing small plastic vials into the bottom. The plastic vials, approximately one inch in diameter by three inches long, were quite efficient in obtaining relatively undisturbed sediment samples.

The distribution patterns of irradiated grains showed extremely rapid rates of dispersion; greater than were expected under such low wave conditions. The transport rate for some particles was as high as 1.5 ft/min during the first ¼-hr period. The initial distribution pattern of surface counts showed dispersion in all directions, with an elongate offshore-onshore axis. In 7 to 24 hr the net onshore transport of sand overshadowed the lateral and offshore dispersion, and the entire surface distribution pattern indicated an onshore migration. Of 26 surface samples collected from the beach at 24 hr, four showed single irradiated particles. The locations of these samples are shown by triangular symbols on the inset of Fig. 1. Both the surface and subsurface samples showed an increase in irradiated grains with time in a shoreward direction, and for the most part the highest counts were found shoreward of the release point at all sampling times.

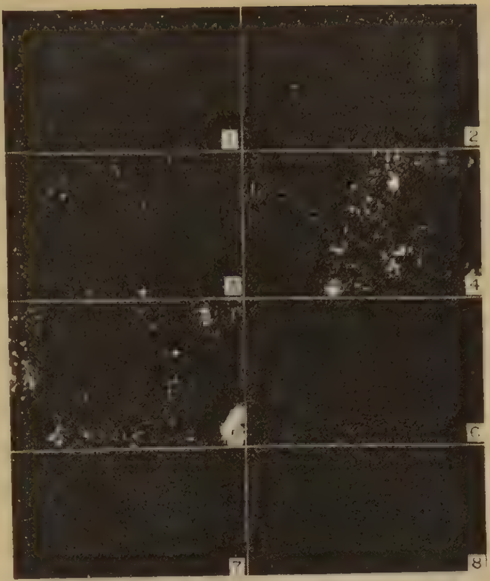

Fig. 4—Eight representative surface samples taken along the onshore-off-shore range line of Figure 2. Samples were taken ¼ hr after the release of irradiated material. These are prints from photosensitive film negatives used in counting the irradiated grains. Each white dot represents one irradiated sand grain. The location of the samples relative to the release point is as follows: (1) 10 ft shoreward, (2) 7½ ft shoreward, (3) 5 ft shoreward, (4) 2½ ft shoreward, (5) 2½ ft seaward, (6) 5 ft seaward, (7) 7½ ft seaward, (8) 10 ft seaward.

The rapid rate of dispersal of sand observed for these relatively quiescent wave conditions may in part result from suspension associated with the alternate erosion and steepening of the 3 to 4-in sand ripples which formed on the bottom. Steep ripples with a height to length ratio of 1:6 were observed to form during the gentle surges accompanying the smaller waves. During the stronger surges accompanying the occasional largest waves (1 to 2-ft in height), these steep ripples were eroded to a more gentle form with a steepness ratio of about 1:12. The first phase in the erosion of the ripples was evidenced by a plume or vortex of suspended sand which extended about six inches above the bottom. For slightly higher wave conditions the ripples are always gentle and thus do not give rise to this type of periodic suspension.

Accurate measurements of the change in sand level were obtained by comparing the length of reference rods exposed along the major axis of the sampling grid, following the procedure of *Inman* and *Rusnak* [1956]. The sand level measurements show that erosion occurred in the vicinity of the release point and that deposition of sand occurred on the beach and, to a lesser extent, offshore (Fig. 2).

The 39 cores taken in the sampling area showed the occurrence of vertical mixing of sand. The subsurface concentration at the release point decreased with time, while the depth of mixed sand increased. At 24 hr, irradiated sand was found as deep as 0.2 ft below the surface of the core taken at the release point. This burying may in part result from the disturbance of previous coring. Cores taken away from the release point showed a decrease in concentration of irradiated material following the one hour sampling, with the exception of cores taken in the onshore direction where a maximum concentration occurred 10 ft from the release point at 7½ hr. A maximum depth of mixing of 0.06 ft was observed at this time.

Summary and conclusions—1. The procedure used in this radioactive tracer experiment was: (*a*) collection of natural sand sample from the area under investigation, (*b*) processing sample to concentrate quartz grains, (*c*) irradiation of processed sample, (*d*) reintroduction of irradiated sample as a point source on the bottom by SCUBA-equipped swimmers, (*e*) collection and assay of samples for radioactive particles by radioautography. The irradiated sand did not constitute an apparent health hazard.

2. The sensitivity for this experiment was one particle per 100,000 particles. However, greater sensitivity is practical and is limited only by size of photosensitive film and size of sample. Sensitivity tests showed that irradiated particles could be detected for periods of several months.

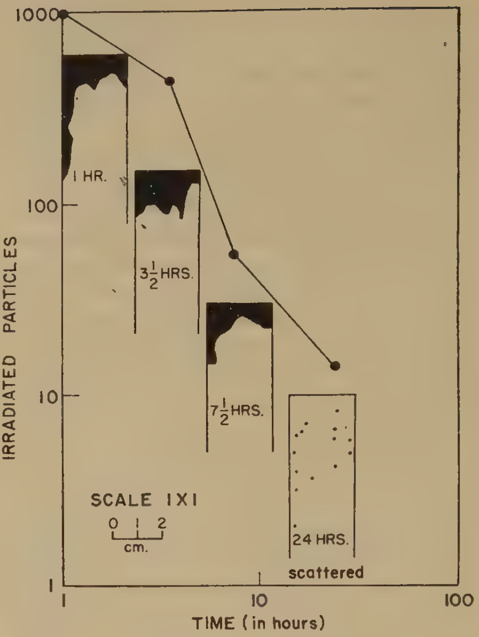

FIG. 5—Concentration of irradiated particles in cores taken at the release point. Vertical distribution of irradiation is shown as black on the diagram of each core. Cores were lithified, sectioned, then exposed to photosensitive film. The extension of the zone of irradiated sand down along the side of the coring tube is the result of coring method.

3. The field experiment indicated a rapid rate of dispersion of sand from the point of release, where the waves were about 1¼ ft high and the water depth was about 10 ft. A net sand transportation rate of 1½ ft/min was measured near the release point.

4. Dispersion of sand was most rapid in the onshore and offshore directions. Irradiated grains were detected on the beach approximately ¼ mi from the release point in 24 hr.

5. Sampling indicated a net onshore transportation of irradiated particles, and that the particles were dispersed over an area as great as 0.75 sq mi in 24 hr (Table 2).

6. Cores near the release point showed

irradiated particles as much as 0.06 ft below the surface of the sand.

7. Measurements of sand level change show that a net erosion of about 0.1 ft occurred in the vicinity of the release point, while deposition of sand occurred on the beach foreshore (Fig. 2). It seems probable that the rate of dispersion of sand would be quite different for irradiated material released in a zone of net deposition.

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REFERENCES

ARLMAN, J. J., P. SANTEMA, AND J. N. SVASEK, Movement of bottom sediment in coastal waters by currents and waves; measurements with the aid of radioactive tracers in the Netherlands, *Deltandienst, Rijkswaterstaat, Ministry of Transport and Waterstaat, The Netherlands, Progress Report*, 1–56, June 1957.

DAVIDSSON, JAN, Investigations of sand movement using radio-active sand, *Lund Studies in Geography Ser., A Physical Geography*, 12, 107–126, 1958.

GOLDBERG, E. D. AND D. L. INMAN, Neutron-irradiated quartz as a tracer of sand movements, *Bulletin of the Geological Society of America*, 66, 611–13, 1955.

HOURS, R., W. D. NESTEROFF, AND V. ROMANOVSKY, Methode d'etude de l'evolution des plages par traceurs radio-actifs, *Centre de Recherches et D'etudes Oceanographiques*, 1, no. 11, 1–7, 1955.

INMAN, D. L., Areal and seasonal variations in beach and nearshore sediments at LaJolla, California, *Beach Erosion Board, Corps of Engineers*, Tech. Memo., no. 39, 1–34, 1953.

INMAN, D. L. AND G. A. RUSNAK, Changes in sand level on the beach and shelf at La Jolla, California, *Beach Erosion Board, Corps of Engineers*, Tech. Memo., no. 79, 1–72, 1956.

INOSE, S. AND N. SHIRAISHI, The measurement of littoral drift by radio-isotopes, *The Dock and Harbour Authority, Hokkaido Development Bureau, Japan*, 284–88, January, 1956.

PUTMAN, J. L. AND D. B. SMITH, Radioactive tracer techniques for sand and silt movements under water, *International Journal of Applied Radiation and Isotopes*, 1, 24–32, 1956.

(Manuscript received August 29, 1958)

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Unusual Conditions in the Pacific

During 1957 and early 1958 it became apparent that the weather, temperatures, and biology of the Pacific were undergoing changes that were quite outside the range of conditions of the last decade or more.

At the invitation of the Scripps Institution of Oceanography, 30 scientists met at Rancho Santa Fe, near San Diego, California, 2–4 June 1958, to consider the nature and causes of the unusual conditions (*1*).

Participants were from institutions on both coasts of North America and from Hawaii, Japan, and Peru, representing research in the fields of meteorology, oceanography, marine biology, and fishery biology, and included persons actively pursuing their research in the Pacific, from the Bering Sea to Peru and westward through the Central Pacific to Japan.

Data considered were the Northern Hemispheric circulation in the atmosphere, sea temperatures, sea level and currents of the Pacific, and the distribution of marine organisms. In addition, the symposium heard a report on the unusual solar events of 1957, when, in September, sun-spot activity reached a 250-year (all-time record) high. The possible relation to the unusual meteorology was discussed.

Another major departure from conditions in immediately preceding years and from those recorded over long-term periods consisted of the unusually strong development and the southeasterly position of the Aleutian low-pressure systems, especially during the winter of 1957–58; these changes produced markedly anomalous wind fields in middle latitudes of the eastern Pacific directed northeastward, and in the northwest Pacific directed southwestward. This was accompanied by unusually high sea temperatures over much of the eastern Pacific, from the Gulf of Alaska to the coasts of Peru. On the other hand, colder sea temperatures extended southward from the Bering Sea along the coast of Japan. Hawaii, during the summer of 1957, failed to experience the usual lowering of salinity connected with the seasonal oscillations of the subtropic convergence system. Sea levels were anomalously high along the West Coast of North America, by an average of 0.5 foot, with the anomaly appearing earliest and most pronouncedly along the coast of southern California. Drift bottles released 500 miles off the coast of British Columbia at latitude 50°N fetched up on beaches rimming the northern shore of the Gulf of Alaska instead of taking their more usual course eastward toward British Columbia, Washington, and Oregon. A strongly developed coastal countercurrent along central and northern California, Oregon, and Washington was evidenced by drift bottles released in California waters.

The diatom and dinoflagellate flora monitored at the Scripps Pier at La Jolla, California, included considerable numbers of tropical forms previously rare or absent. Southern forms also were found far north of their expected range in California waters. Certain species of salps ordinarily confined to waters off southern California extended northward in coastal waters well beyond Point Conception, as did also certain euphausiids of similar normal range. Species of these two groups, which normally occupy the oceanic mid-Pacific waters, apparently did not spread eastward towards the North American coasts, however. As for the fishes, there were a number of records from farther north of tropical and subtropical species, and two species, the barracuda and yellowtail, usually caught by sportsmen in moderate numbers off southern California, were taken in numbers larger by an order of magnitude than the usual number. Dolphin fish were taken in entirely unprecedented numbers. Sardine spawning, which in the preceding 7-year period had been largely confined to waters off Lower California, in 1957 and 1958 took place in southern California waters. There was an indication that, in 1958, the pelagic phyllosome larvae of the spiny lobster were being better retained in the waters of southern California than in previous years.

The long-term records of such meteorological and oceanographic data as have been recorded systematically suggested that the conditions of 1957 and the winter of 1957–58 represented a marked reversal of conditions which had persisted during the previous decade and resembled roughly the conditions usual during the decade of the 1930's. The year 1958 appeared, at the time of this writing, to resemble the unusual years of 1926, 1931, and 1941.

Extensive consideration of theoretical models and empirical oceanographic observations led to the conclusion that the phenomena observed during 1957, which reached their peak in the winter of 1957–58, were undoubtedly the evidence of large-scale advection of water masses, but that the theory and the data so far analyzed are inadequate to distinguish the processes by which this advection took place. Particularly in question was the relative influence of transport from the offshore direction as compared with the transport alongshore from the south. The coastal countercurrent (sometimes called the Davidson Current) was more highly developed than in the immediately preceding years, but the mechanisms involved, and the role the coastal countercurrent played in the changed temperature field, remained obscure. Likewise, speculation on a possible displacement of the zonal North Pacific current system failed to produce an entirely satisfactory explanation.

In view of the obviously inadequate state of oceanographic observations and theory, it was felt that the conditions of 1957 and of the winter of 1957–58 should furnish strong motivation for determined efforts to evolve theories in conjunction with direct measurements of water movements and continued dynamic measurements on a much wider scale.

The symposium emphasized the point that local changes of conditions cannot be studied provincially but are part of Pacific-wide or possibly world-wide changes.

The proceedings of the symposium are to be published, and are to be dedicated to Bell Shimada and Townsend Cromwell, whose tragic and untimely deaths in an aircraft accident in Mexico occurred during the symposium.

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Note

1. This report is a contribution from the Scripps Institution of Oceanography. It is based on a report to the American Society of Limnology and Oceanography, Logan, Utah, of 18 June 1958.

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Flow estimate for the perpetual salt fountain

GORDON W. GROVES

(Received 25 July 1958)

STOMMEL *et al.* (1955) pointed out the " perpetual salt fountain " as an interesting oceanographical curiosity that might possibly be used for pumping up nutrient-rich deep water to the surface for ocean farming applications. The fountain would work in a region where there is a salinity minimum below the warm surface layer of the ocean. STOMMEL *et al.* state, " If a long tube were lowered from the surface to depth of low salinity water, and the deep water were slowly pumped to the surface through the tube, and the pump then disconnected, the water would continue to flow, by itself, forever. This remarkable phenomenon occurs because slow motion through the tube allows the water inside to attain the same temperature as the surrounding water. Its salinity, and hence density, is therefore less than that of its surroundings outside the tube, and hence the entire column of water inside the tube is buoyant with respect to the fluid outside at the same level. If the direction of pumping is reversed, so that the fluid initially goes downward, it will of course continue to flow downward forever on account of its excess in density over that of the water outside the tube."

In order to estimate the rate of flow in the salt fountain, let us assume that a straight tube of length L extends slanting from the surface to a depth h in a horizontally stratified ocean. The vertical co-ordinate y is taken positive downward and zero at the surface, and $\theta(y)$ and $S(y)$ represent the temperature and salinity, respectively, of the ocean. Inside the tube the salinity is uniformly equal to $S(h)$ for upward flow and the temperature is designated by $\phi(y)$, steady state being assumed. Taking the temperature inside the tube as a function only of y presupposes complete mixing in any horizontal layer and leads to a slight over-estimate of heat conduction and hence flow rate especially in the case of laminar flow, but this will not seriously affect the results. The water density inside and outside the tube is taken as a linear function of temperature and salinity,

$$\rho = \rho_0 + \theta \frac{\partial \rho}{\partial \theta} + S \frac{\partial \rho}{\partial S} \tag{1}$$

compressibility effects being neglected. The coefficients $\frac{\partial \rho}{\partial \theta}$ and $\frac{\partial \rho}{\partial S}$ are taken as constants.

The temperatures inside and outside the tube are related by the equation

$$\frac{D\phi}{Dt} \equiv -\frac{vh}{L}\frac{d\phi}{dy} = \frac{2n}{w\rho cr}(\theta - \phi), \qquad \phi(h) = \theta(h) \tag{2}$$

where v is average velocity of flow through tube toward the sea surface, n is heat conductivity of tube material, c is specific heat of the sea-water, w is the wall thickness

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and r the inside radius of the tube. Here r is assumed very large compared to w. D/Dt designates the material derivative following the mean motion of the water. Equation (2) has the solution

$$\phi(y) = \gamma e^{\gamma y} \int_y^h \theta(y') e^{-\gamma y'} dy' + \theta(h) e^{-\gamma(h-y)} \tag{3}$$

where

$$\gamma = 4\, nL/w\rho c v R h, \qquad R = 2\, vr/\nu$$

ν being the (constant) kinematic viscosity of the sea-water.

If we assume that the water is removed from the top of the tube as fast as it flows up, so that no additional head is formed, the excess of pressure at the bottom end of the tube over the hydrostatic head of water inside the tube is

$$\Delta p = g \int_0^h \left\{ [S(y) - S(h)] \frac{\partial \rho}{\partial S} + [\theta(y) - \phi(y)] \frac{\partial \rho}{\partial \theta} \right\} dy \tag{4}$$

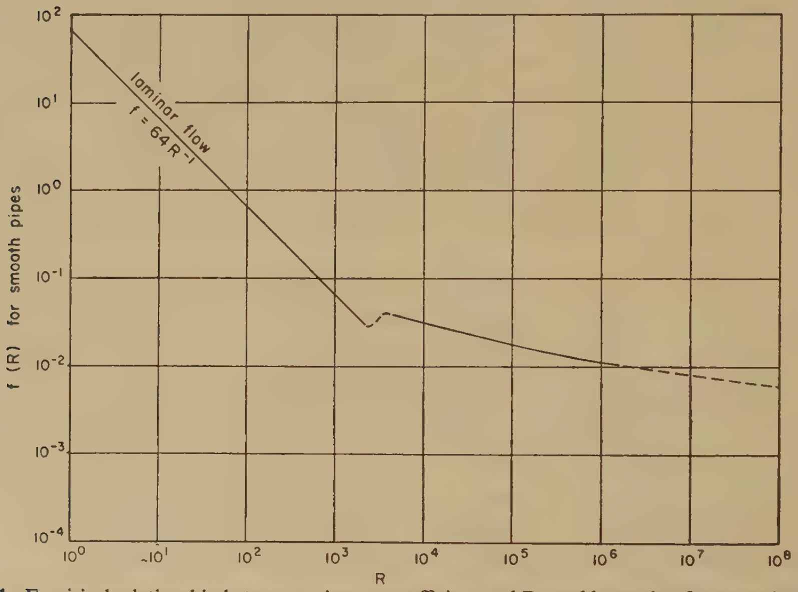

Fig. 1. Empirical relationship between resistance coefficient and Reynolds number for smooth pipes.

This pressure difference is balanced by friction of flow through the tube. The stress τ on the tube's inner surface depends only on the Reynolds number R and the character of the tube's roughness. We shall consider only the case of a perfectly smooth tube. The relation is usually expressed in the form

$$\tau = \tfrac{1}{8} f(R)\, \rho v^2 \tag{5}$$

where $f(R)$ is called the "resistance coefficient' (see, for example, ROUSE, 1938). The empirical relationship between resistance coefficient for smooth tubes and Reynolds number is shown in Fig. 1. The total pressure drop resulting from flow resistance, $\Delta p = 2L\tau/r$, must be equated to expression (4) to determine the flow rate, but first the temperature profile in the ocean must be specified.

The simplest temperature profile is the case of constant temperature down to the tube's tip, which is just immersed in water of lower temperature. Accordingly, we take

$$\theta(y) = \theta_0 \qquad \text{for} \qquad 0 < y < h$$

$$\theta(h) = \theta_h$$

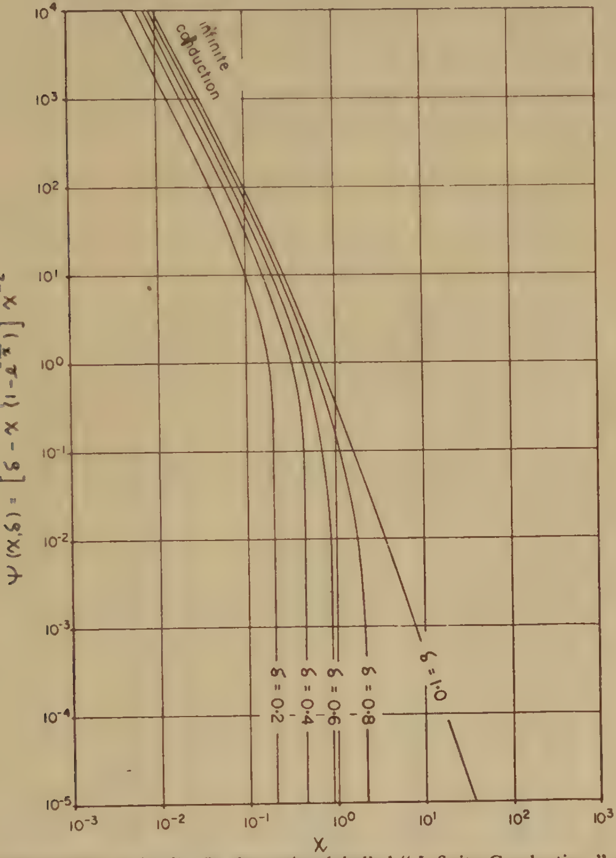

Fig. 2. Plot of the function $\psi(x, \delta)$. In the region labelled "Infinite Conduction," the function is approximately equal to δ/x^2.

For this case the salt fountain will flow perpetually only in the upward direction. Relations (3), (4) and (5) then give

$$f(R) = \alpha^2 \beta\, \psi(x, \delta) \tag{6}$$

where

$$\psi(x, \delta) = x^{-2}\,[\delta + x\,(e^{-1/x} - 1)] \tag{7}$$

and

$$x = \alpha R, \qquad \alpha = w\rho c v/4nL$$

$$\beta = \frac{16\,g r^3}{v^2}\,\frac{h}{L}\left(\frac{\Delta\rho}{\rho}\right)_\theta, \qquad \delta = \left(\frac{\Delta\rho}{\rho}\right)_S \Big/ \left(\frac{\Delta\rho}{\rho}\right)_\theta$$

$$\left(\frac{\Delta\rho}{\rho}\right)_S = \frac{\bar{S} - S(h)}{\rho}\frac{\partial\rho}{\partial S}, \qquad \left(\frac{\Delta\rho}{\rho}\right)_\theta = -\frac{\theta_0 - \theta_h}{\rho}\frac{\partial\rho}{\partial\theta}, \qquad \bar{S} = \frac{1}{h}\int_0^h S(y)\,dy.$$

In order for the fountain to work we must have $\delta > 0$, and for stability we must have $\delta < 1$. The function $\psi(x, \delta)$ is shown plotted in Fig. 2. Equation (6) shows that the flow is determined by the three nondimensional parameters, α, β, δ only. The equation is solved graphically for the Reynolds number R very easily for any given set of the parameters α, β, δ by overlaying the plots in Figs. 1 and 2. The following table of values of R was constructed in that way :

Table 1. *Values of Reynolds Number*

α/β	10^5	10^6	10^7	10^8	10^9	δ
10^{-9}					$1{\cdot}1 \times 10^5$	0·2
					$1{\cdot}6 \times 10^5$	0·4
					$2{\cdot}0 \times 10^5$	0·6
					$2{\cdot}3 \times 10^5$	0·8
					$2{\cdot}6 \times 10^5$	1·0
10^{-8}		$2{\cdot}6 \times 10^3$	$7{\cdot}6 \times 10^3$	$2{\cdot}8 \times 10^4$	$1{\cdot}0 \times 10^5$	0·2
		$3{\cdot}2 \times 10^3$	$1{\cdot}2 \times 10^4$	$4{\cdot}2 \times 10^4$	$1{\cdot}6 \times 10^5$	0·4
		$4{\cdot}0 \times 10^3$	$1{\cdot}4 \times 10^4$	$5{\cdot}2 \times 10^4$	$1{\cdot}9 \times 10^5$	0·6
		$4{\cdot}6 \times 10^3$	$1{\cdot}7 \times 10^4$	$6{\cdot}3 \times 10^4$	$2{\cdot}2 \times 10^5$	0·8
		$5{\cdot}2 \times 10^3$	$2{\cdot}0 \times 10^4$	$7{\cdot}1 \times 10^4$	$2{\cdot}6 \times 10^5$	1·0
10^{-7}		$2{\cdot}6 \times 10^3$	$6{\cdot}8 \times 10^3$	$2{\cdot}8 \times 10^4$	$1{\cdot}0 \times 10^5$	0·2
		$3{\cdot}2 \times 10^3$	$1{\cdot}1 \times 10^4$	$4{\cdot}1 \times 10^4$	$1{\cdot}6 \times 10^5$	0·4
		$3{\cdot}8 \times 10^3$	$1{\cdot}4 \times 10^4$	$5{\cdot}2 \times 10^4$	$1{\cdot}9 \times 10^5$	0·6
		$4{\cdot}5 \times 10^3$	$1{\cdot}7 \times 10^4$	$6{\cdot}2 \times 10^4$	$2{\cdot}3 \times 10^5$	0·8
		$5{\cdot}1 \times 10^3$	$1{\cdot}9 \times 10^4$	$7{\cdot}1 \times 10^4$	$2{\cdot}6 \times 10^5$	1·0
10^{-6}	$3{\cdot}0 \times 10^2$	$2{\cdot}5 \times 10^3$	$7{\cdot}4 \times 10^3$	$2{\cdot}7 \times 10^4$	$7{\cdot}9 \times 10^4$	0·2
	$5{\cdot}9 \times 10^2$	$3{\cdot}2 \times 10^3$	$1{\cdot}1 \times 10^4$	$4{\cdot}0 \times 10^4$	$1{\cdot}3 \times 10^5$	0·4
	$8{\cdot}5 \times 10^2$	$3{\cdot}7 \times 10^3$	$1{\cdot}4 \times 10^4$	$4{\cdot}9 \times 10^4$	$1{\cdot}6 \times 10^5$	0·6
	$1{\cdot}2 \times 10^3$	$4{\cdot}5 \times 10^3$	$1{\cdot}7 \times 10^4$	$5{\cdot}9 \times 10^4$	$2{\cdot}0 \times 10^5$	0·8
	$1{\cdot}5 \times 10^3$	$5{\cdot}0 \times 10^3$	$1{\cdot}9 \times 10^4$	$6{\cdot}9 \times 10^4$	$2{\cdot}3 \times 10^5$	1·0
10^{-5}	$2{\cdot}9 \times 10^2$	$2{\cdot}5 \times 10^3$	$6{\cdot}3 \times 10^3$	$1{\cdot}5 \times 10^4$	$2{\cdot}0 \times 10^4$	0·2
	$5{\cdot}8 \times 10^2$	$3{\cdot}2 \times 10^3$	$1{\cdot}0 \times 10^4$	$2{\cdot}5 \times 10^4$	$4{\cdot}2 \times 10^4$	0·4
	$8{\cdot}5 \times 10^2$	$3{\cdot}6 \times 10^3$	$1{\cdot}2 \times 10^4$	$3{\cdot}4 \times 10^4$	$6{\cdot}3 \times 10^4$	0·6
	$1{\cdot}2 \times 10^3$	$4{\cdot}3 \times 10^3$	$1{\cdot}5 \times 10^4$	$4{\cdot}2 \times 10^4$	$1{\cdot}0 \times 10^5$	0·8
	$1{\cdot}4 \times 10^3$	$5{\cdot}0 \times 10^3$	$1{\cdot}7 \times 10^4$	$5{\cdot}1 \times 10^4$	$1{\cdot}3 \times 10^5$	1·0
10^{-4}	$2{\cdot}8 \times 10^2$	$1{\cdot}3 \times 10^3$	$2{\cdot}0 \times 10^3$	$2{\cdot}0 \times 10^3$	$2{\cdot}0 \times 10^3$	0·2
	$5{\cdot}5 \times 10^2$	$2{\cdot}4 \times 10^3$	$3{\cdot}8 \times 10^3$	$4{\cdot}5 \times 10^3$	$4{\cdot}5 \times 10^3$	0·4
	$7{\cdot}9 \times 10^2$	$3{\cdot}0 \times 10^3$	$5{\cdot}6 \times 10^3$	$7{\cdot}9 \times 10^3$	$8{\cdot}9 \times 10^3$	0·6
	$1{\cdot}1 \times 10^3$	$3{\cdot}5 \times 10^3$	$7{\cdot}9 \times 10^3$	$1{\cdot}5 \times 10^4$	$2{\cdot}0 \times 10^4$	0·8
	$1{\cdot}3 \times 10^3$	$4{\cdot}0 \times 10^3$	$1{\cdot}0 \times 10^4$	$2{\cdot}6 \times 10^4$	$6{\cdot}2 \times 10^4$	1·0
10^{-3}	$1{\cdot}3 \times 10^2$	$2{\cdot}0 \times 10^2$	$2{\cdot}0 \times 10^2$	$2{\cdot}0 \times 10^2$	$2{\cdot}0 \times 10^2$	0·2
	$2{\cdot}5 \times 10^2$	$4{\cdot}4 \times 10^2$	$4{\cdot}5 \times 10^2$	$4{\cdot}5 \times 10^2$	$4{\cdot}5 \times 10^2$	0·4
	$3{\cdot}8 \times 10^2$	$7{\cdot}2 \times 10^2$	$8{\cdot}9 \times 10^2$	$8{\cdot}9 \times 10^2$	$8{\cdot}9 \times 10^2$	0·6
	$5{\cdot}2 \times 10^2$	$1{\cdot}3 \times 10^3$	$2{\cdot}0 \times 10^3$	$2{\cdot}1 \times 10^3$	$2{\cdot}1 \times 10^3$	0·8
	$7{\cdot}1 \times 10^2$	$2{\cdot}5 \times 10^3$	$5{\cdot}0 \times 10^3$	$1{\cdot}1 \times 10^4$	$2{\cdot}7 \times 10^4$	1·0
10^{-2}	$2{\cdot}0 \times 10^1$	$2{\cdot}0 \times 10^1$	$2{\cdot}0 \times 10^1$	$2{\cdot}0 \times 10^1$	$2{\cdot}0 \times 10^1$	0·2
	$4{\cdot}4 \times 10^1$	$4{\cdot}5 \times 10^1$	$4{\cdot}5 \times 10^1$	$4{\cdot}5 \times 10^1$	$4{\cdot}5 \times 10^1$	0·4
	$7{\cdot}2 \times 10^1$	$8{\cdot}9 \times 10^1$	$8{\cdot}9 \times 10^1$	$8{\cdot}9 \times 10^1$	$8{\cdot}9 \times 10^1$	0·6
	$1{\cdot}3 \times 10^2$	$2{\cdot}0 \times 10^2$	$2{\cdot}1 \times 10^2$	$2{\cdot}1 \times 10^2$	$2{\cdot}1 \times 10^2$	0·8
	$2{\cdot}7 \times 10^2$	$8{\cdot}7 \times 10^2$	$2{\cdot}6 \times 10^3$	$5{\cdot}0 \times 10^3$	$1{\cdot}1 \times 10^4$	1·0
10^{-1}	$2{\cdot}0 \times 10^0$	$2{\cdot}0 \times 10^0$	$2{\cdot}0 \times 10^0$	$2{\cdot}0 \times 10^0$	$2{\cdot}0 \times 10^0$	0·2
	$4{\cdot}5 \times 10^0$	$4{\cdot}5 \times 10^0$	$4{\cdot}5 \times 10^0$	$4{\cdot}5 \times 10^0$	$4{\cdot}5 \times 10^0$	0·4
	$8{\cdot}9 \times 10^0$	$8{\cdot}9 \times 10^0$	$8{\cdot}9 \times 10^0$	$8{\cdot}9 \times 10^0$	$8{\cdot}9 \times 10^0$	0·6
	$2{\cdot}0 \times 10^1$	$2{\cdot}1 \times 10^1$	$2{\cdot}1 \times 10^1$	$2{\cdot}1 \times 10^1$	$2{\cdot}1 \times 10^1$	0·8
	$8{\cdot}9 \times 10^1$	$2{\cdot}8 \times 10^2$	$8{\cdot}9 \times 10^2$	$2{\cdot}5 \times 10^3$	$5{\cdot}0 \times 10^3$	1·0

(14)

The five R values listed for each pair of α, β values corresponds to δ values of 0·2, 0·4, 0·6, 0·8, 1·0, respectively, reading from top to bottom. The mean flow velocity v or volume rate of flow Q can be found from the definition of the Reynolds number ; we have

$$v = \frac{\nu}{2r} R, \qquad Q = \frac{\pi}{2} r \nu R \tag{8}$$

For a large range of values the flow is laminar ($R < 2{,}000$), and also for a large range of conditions the flow of heat into the tube is so fast compared to the fluid velocity up the tube that the temperature of the water inside the tube is essentially equal to that of the outside sea-water. For these conditions to be fulfilled, we must have

$$\beta\delta < 1{\cdot}3 \times 10^5, \qquad \alpha\beta < 6 \tag{9}$$

respectively. The Reynolds number is then given by the simple expression

$$R = \beta\delta/64$$

which enables one to extend the range of computations beyond that encompassed by Table 1.

To take a numerical example, consider a copper tube ($n \simeq 1{\cdot}0$ cal cm deg^{-1} sec^{-1}) with

$h = 300$ m $\qquad \nu = 0{\cdot}01$ cm^2 sec^{-1}

$L = 600$ m $\qquad \bar{S} - S(h) = 0{\cdot}5$ parts per mil

$w = 2{\cdot}0$ mm $\qquad \theta_0 - \theta_h = 6$°C

$\rho = 1{\cdot}0$ gm cm^{-3} $\qquad \partial\rho/\partial\theta = -2 \times 10^{-4}$ gm cm^{-3} deg^{-1}

$c = 1{\cdot}0$ cal gm^{-1} deg^{-1} $\qquad \partial\rho/\partial S = 7 \times 10^{4}$ gm cm^{-3} per part per mil

$r = 10$ cm $\qquad g = 10^3$ cm sec^{-2}

We then compute

$$\left(\frac{\Delta\rho}{\rho}\right)_S = 3{\cdot}5 \times 10^{-4}, \quad \left(\frac{\Delta\rho}{\rho}\right)_\theta = 12 \times 10^{-4}, \quad \alpha = 8{\cdot}3 \times 10^{-9}, \quad \beta = 9{\cdot}6 \times 10^7, \quad \delta = 0{\cdot}29$$

The first (laminar flow) condition (9) is not satisfied. Taking $\alpha = 10^{-8}$, $\beta = 10^8$ and interpolating for δ in Table 1, we arrive at the estimate, $R = 3{\cdot}5 \times 10^4$, $v = 17{\cdot}5$ cm sec^{-1}, $Q = 5{\cdot}5$ litres per sec. This is an impressive rate of flow, resulting largely from the intense salinity minimum assumed.

Let us consider the rate at which the total mass of fish might increase in a nutrient-starved reservoir equipped with a " salt fountain " under the above conditions. We shall assume that phosphorus is the only factor limiting organic production, and that the concentration of inorganic phosphorus at the lower end of the tube (at depth of 300 m) is 2·5 μg atoms/L. It has been estimated (FLEMING, 1940) that the general carbon to phosphorus mass ratio in plankton is 41 : 1. However, a very small portion of the total organic material resulting from the additional flow of phosphorus exists in the bodies of edible fish. Estimates vary widely, but a value of 1 per cent for the ratio of organic carbon in edible fish to total organic carbon falls in the range of probable values. The wet weight of a fish is about 10 times the weight of its organic carbon (VINOGRADOV, 1953). Then, under the above assumptions, 54 kg/year of edible fish will be " produced " by the addition of 5·5 L/sec of nutrient-rich water. This seems like a small reward for the effort. The same amount of phosphorus could be added by dumping in 290 kg/year of Peruvian guano*, whose phosphorus content is 4·6 per cent (Cia. Administradora del Guano, 1956).

In view of the above example, it appears that STOMMEL *et al.* were correct in describing the perpetual salt fountain as an " oceanographical curiosity."

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REFERENCES

COMPAÑÍA ADMINISTRADORA DEL GUANO, (1956) Memoria Anual, Lima, Peru.
FLEMING R. H. (1940) Composition of plankton and units for reporting populations and production. Proceedings of the Sixth Pacific Science Congress 3, pp. 535-540.
ROUSE H. (1938) *Fluid mechanics for hydraulic engineers.* McGraw-Hill New York and London.
STOMMEL H., ARONS A. B. and BLANCHARD D. (1955) An oceanographical curiosity : the perpetual salt fountain. *Deep Sea Res.* **3**, (2), 152-153.
VINOGRADOV A. P. (1953) The elementary chemical composition of marine organisms. Sears Foundation for Marine Research, Memoir, **2**, 647 pp.

*In the above computation, if the tube's radius and wall thickness were 100 cm and 5 mm, respectively, all other conditions remaining the same, the computed flow rate would be about 3,000 litres per second, approximately equivalent to dumping in 160 metric tons of guano per year, and an annual production of 30 tons wet weight of fish.

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The Distribution of the Planktonic Chaetognatha in the Pacific and their Relationship to the Water Masses[1]

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ABSTRACT

The geographic extents of 27 species of Chaetognatha in the Pacific have been inferred from analyses of 2,900 plankton samples taken at more than 900 stations.

Two species of chaetognaths—*Sagitta elegans* and *S. maxima*—are found in the Pacific only in the Subarctic Water Mass. Four species—*Sagitta enflata*, *S. hexaptera*, *S. pacifica*, and *Pterosagitta draco*—occur in the Pacific Equatorial and Central Water Masses. Seven species—*Sagitta robusta*, *S. regularis*, *S. ferox*, *Krohnitta pacifica*, *Sagitta bedoti*, *S. neglecta*, and *S. pulchra*—occur in the Equatorial and Western Central Water Masses. The latter three species appear to be disjunct equatorial species that are absent from the central equatorial Pacific. *Sagitta pseudoserratodentata* occupies the North Pacific Central Water Mass. *S. californica*, essentially a warm-water cosmopolite, is very rare in the Equatorial Water Mass. The Peru and California Currents are inhabited by *Sagitta friderici*. A close relative, *S. crassa*, lives in the coastal waters of Japan. *Sagitta minima*, *Sagitta* species (*serratodentata* group), *Sagitta decipiens*, *S. lyra*, and *Krohnitta subtilis*, species which have their maximum abundance at about 200 meters (somewhat deeper than all of the preceding), appear to be limited in the north at about 45° N. Lat. *Sagitta planctonis*, *S. macrocephala*, and *Eukrohnia fowleri*, living primarily at depths of 500 meters and greater, have been taken in the present study as far north as 55° N. Lat., both in the Bering Sea and Gulf of Alaska. The very deep living species, *Heterokrohnia mirabilis*, was taken at a single station in the Eastern Equatorial Pacific. The sharpest chaetognath boundary yet found in the Pacific occurs in the Eastern Pacific at 18° to 20° N. Lat. and is associated with pronounced temperature, oxygen, and probably salinity gradients.

Species distributions analogous to those of the Chaetognatha are found in the euphausiids, copepods, and dinoflagellates among other groups of organisms.

INTRODUCTION

Since the first chaetognath was described in 1778 by the Dutch worker, Martin Slabber, more than five-hundred papers have been published that deal wholly or in part with this group of marine animals. In the past 25 years there has been a considerable increase in the amount of work on the Chaetognatha. This accelerated interest is due chiefly to a series of papers published by F. S. Russell between 1932 and 1939, in which he related the distribution of *Sagitta elegans* and *S. setosa* to good and poor years of herring spawning in the vicinity of the English Channel. Russell emphasized the use of chaetognaths as current indicators in that region, although the relationship of *S. elegans* and *S. setosa* to the water masses around England was set forth in an earlier work (Meek 1928) to which Russell did not refer.

The concept of using pelagic animals and the larvae of benthic organisms as indicators of water movement is at least as old as the era of the Challenger Expedition. For example, Agassiz (1883), writing of the

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pelagic coelenterates *Porpita*, *Velella*, and *Physalia*, said, "In fact these surface animals are excellent guides to the course of the current of the Gulf Stream,—natural current bottles, as it were." Fraser (1952) summarized some of the advantages as well as some of the problems of the modern work in this field. However, it must be admitted that indicator work is still largely based on qualitative methods and intuitive interpretations. There are as yet no formalized procedures or general agreement on techniques.

At the present time at least 24 scientists in ten countries, nearly three-fourths of them employed by government fishery research institutions, are working primarily on the Chaetognatha. Despite the comparatively large literature that has accumulated and the recent increase in interest in the group, it is not possible today to describe with any degree of confidence the limits or range in any ocean of more than one or two of the more than 40 known species. In view of the fact that indicator studies are based largely on variations in the geographic borders or limits of species, it is evident that such work is still in its infancy. The present study is a beginning at filling part of this void in our knowledge of the Chaetognatha in the Pacific.

From 1950 through 1955 the author examined the chaetognaths taken in plankton samples collected during more than 35 expeditions and routine marine life surveys in the North Pacific, in the equatorial regions of the South Pacific, and in the Beaufort-Chukchi Sea region of the Arctic. In the reduction and analysis of the accumulated data, it became evident that the findings for local areas could be properly interpreted only when compared to the findings for neighboring regions. Consequently, before publishing the detailed results from local regions, an overall picture of the distribution of the various species was worked out, insofar as the data and the published findings of other workers permitted. This general treatment is presented herein.

The author wishes to extend his sincere thanks to Professor Martin W. Johnson of the Scripps Institution, for his continued interest in and support of the author's research. I also wish to thank Drs. Thomas E. Bowman, Brian P. Boden, and Warren S. Wooster for their stimulating help in the beginning phases of this study. Discussions with Dr. Bowman, and Messrs. Edward Brinton, John S. Bradshaw, John A. McGowan, and Leo D. Berner, comparing their findings on other zooplankton groups with the Chaetognatha have been particularly helpful. Dr. Martin W. Johnson, Dr. Carl L. Hubbs, Mr. Stacey D. Hicks, Dr. E. Lowe Pierce, Dr. Takasi Tokioka, Dr. Fred B. Phleger, Dr. Robert S. Arthur, Dr. Joel W. Hedgpeth, and Dr. Norris W. Rakestraw made many helpful suggestions in reviewiig the manuscript. Mr. Townsend Cromwell kindly supplied the physical-chemical data from which Figures 24–26 were prepared.

This research was partially supported by the California Cooperative Oceanic Fisheries Investigations. One cannot adequately thank all those who took part in the difficult and at times hazardous task of collecting the samples which are the basis of this report.

PREVIOUS WORK IN THE PACIFIC

Four papers (Michael 1911; Tokioka 1939a, 1940a; Thomson 1947) stand out as the major contributions to our knowledge of the Chaetognatha in the Pacific. Thomson listed the papers on chaetognaths applicable to the geographic regions of the Pacific, to 1947. Some papers which he overlooked are the following. Baldasseroni (1915) reported on the species found on a trip from Valparaiso to Panama to Sydney, and Grey (1931) listed some chaetognath species from the Society Islands. Bigelow and Leslie (1930), in describing the hydrography and plankton in Monterey Bay, give the occurrence of several chaetognath species there. Papers by Dakin and Colefax (1940), Schilp (1941), Hsü (1943), and Mawson (1944) list various species of chaetognaths found in the western Pacific. Wailes (1929) first reported on the Chaetognatha from British Columbia. Although listed in Thomson's bibliography, papers by Russell (1934) and Grey (1922) are not included in his geographic summary.

(18)

Since Thomson's 1947 work, Tokioka has published several papers (1951, 1954a, 1954b, 1955a, 1955b, and 1956) dealing primarily with the occurrence of the Chaetognatha in the western Pacific, and Lea (1955) has added to our knowledge of the chaetognaths off British Columbia. Tchindonova (1955) has reported on the chaetognaths from the Kurile-Kamchatka Trench, and Bieri (1957) has given the first indication of the species to be found in the southeast Pacific. Other recent papers are those of Kusmorskaya (1949), Sproston (1949), Uyeno (1952), Maurice (1953), Thomson (1954), Hamon (1956), and Hida (1957).

MATERIAL

The 2,900 plankton samples that form the basis of this report were collected from more than 950 stations, mostly on cruises of the ships of the Scripps Institution of Oceanography, of the University of California. Many of the cruises were an integral part of the Marine Life Research Program of the California Cooperative Oceanic Fisheries Investigations. These extensive investigations off the California Coast were supplemented by a series of longer-ranging expeditions carried out by the Scripps Institution. In addition, many samples collected on vessels of the United States Navy and by the Pacific Oceanic Fisheries Investigations of the United States Fish and Wildlife Service were examined (Table 1 and Fig. 1).

Of the more than 950 stations involved, 720 are located by dots on the species distribution charts that follow. Stations off Baja California, California, Oregon, in the

TABLE 1. *Plankton samples analyzed for chaetognath species*

Expedition	Depth of tow in meters	No. of one-meter net samples	No. of trawls	No. other plankton samples
Mid-Pacific 1950	0–100, 0–1000	6	28	38
Northern Holiday 1951	0–200	55	21	
Shellback 1952	0–300	203	18	
Long Line 1953	0–300	26		
Capricorn 1953	0–140	33		
Transpacific 1953	0–150, 150–300, 300–450, 450–600, 0–1000	333		
Troll 1955	0–200	85		
Pacific Oceanic Fisheries Investigations, Cruise 5 1950 (POFI)	0–200	51		
POFI Cruise 8 1951	0–200	87		
Pelagic Area Studies 1954	0–25, 25–50, 50–75, 75–100, 100–300, 300–500, 500–700	138		50
U. S. S. Nereus 1947	0–100, 0–200			28
U. S. S. Burton Isl. 1950 (Chukchi and Beaufort Seas)	0–100			53
U. S. S. Burton Isl. 1951 (Bering Sea)	0–50			10
U. S. S. Burton Isl. 1951 (Beaufort Sea)	0–100			56
U. S. S. Burton Isl. 1953 (Pr. Wales Str.)	0–100			30
U. S. C. G. C. North Wind 1954 (Banks Isl.)	0–50			21
Chinook 1956	0–100	9		
Equapac 1956	0–300	40		
Marine Life Res. 1939 (MLR)	0–60, 60–120	32		
MLR 1941	0–100	108		
MLR 1949–1954	0–70, 0–140	1059		
MLR 1950 (deep)	0–600, 0–1000	65		
Miscellaneous 1933–1951		95		168
Total......................		2425	67	454

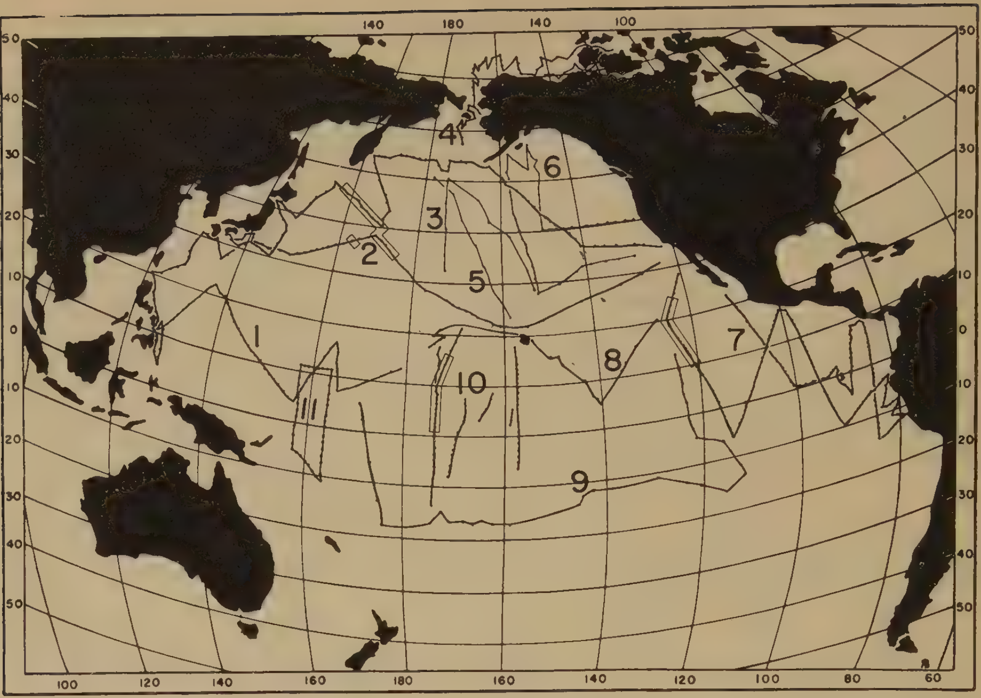
140
180
140
100
1
2
3
4
5
6
7
8
9
10
11
50
40
30
20
10
0
10
20
30
40
50
100
120
140
160
180
160
140
120
100
80
60

FIG. 1. Generalized tracks of the major expeditions reported in this paper. (1) Troll, (2) Transpacific, (3) Chinook, (4) U. S. S. Burton Island, (5) U. S. S. Nereus, (6) Northern Holiday, (7) Shellback, (8) Midpacific, (9) Capricorn, (10) Pacific Oceanic Fisheries Investigations, (11) Equapac. Locations of temperature, salinity, and oxygen sections shown in Figures 24–26, from Transpacific Expedition and Station No. 112, are indicated by blocked areas.

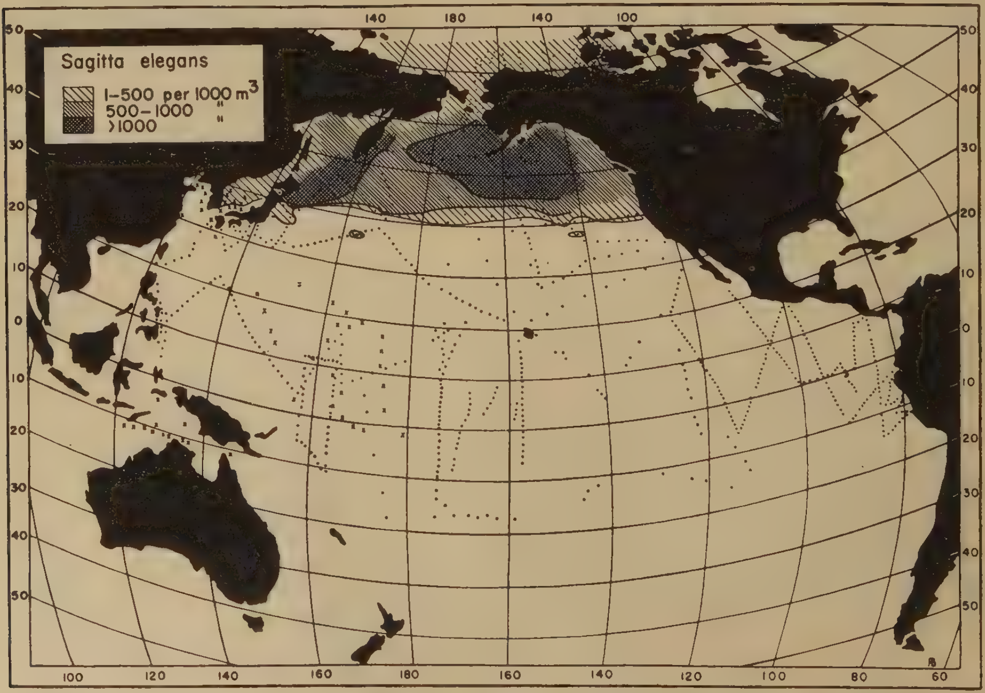
Sagitta elegans
1–500 per 1000 m3
500–1000 "
>1000 "
140
180
140
100
50
40
30
20
10
0
10
20
30
40
50
100
120
140
160
180
160
140
120
100
80
60

FIG. 2. Distribution of *Sagitta elegans* in the Pacific and regions to the north. X's are stations reported by Tokioka 1940a, 1940b, 1942, 1951, 1955a, and 1956. The species was found only in the shaded area.

Gulf of California, and some of the stations off Peru, Japan, and the Philippines are not located on the charts because of the close spacing of the stations in those areas. For the same reason only 40 of about 150 stations in the Arctic between 110° and 165° W. Long. are charted. The intensity of sampling at the stations varied from 1 to 18 net tows per station at any one time, and many stations were occupied two or more times.

Station locations, dates, times, and depth of tows for the Pacific Oceanic Fisheries Investigations are given in King and Demond (1953), for the Marine Life Research cruises in Staff, South Pacific Fisheries Investigations (1954), for Long Line Expedition in Wooster and Jennings (1955), and for the U.S.S. Burton Island Expeditions in Johnson (1956). Mimeographed lists of the station locations, dates, times and depths of tows for Transpacific, Pelagic Area Studies, Shellback, Northern Holiday, Chinook, Troll, Capricorn, and Mid-Pacific Expeditions are available in the Division of Marine Invertebrates, Scripps Institution of Oceanography. A summary of the original data on which this paper is based is deposited in the Library of the Scripps Institution. Identified specimens of most of the species discussed have been deposited in the Division of Marine Invertebrates of Scripps Institution and in the United States National Museum (U.S.N.M. catalog numbers 28688 through 28705).

FIELD OPERATIONS

Several types of nets were used to collect the samples, at various depths and in different ways (Table 1). Most of the one-meter nets were equipped with current meters and usually filtered about 1,000 cubic meters of water per tow. The one-meter nets had a mesh of 0.65 mm (#30 xxx silk grit gauze). The one-half meter nets were of varying mesh sizes of which the most common was 0.2 mm. The great majority of net tows were oblique from the stated depths to the surface. However, on Transpacific Expedition and Pelagic Area Studies, opening-closing nets were used in oblique tows so that the water column was divided into the indicated depth intervals. The construction and use of the one-meter nets are described in greater detail by the Staff, South Pacific Fishery Investigations (1952, 1953, 1954, 1955) and by King and Demond (1953). In the Arctic regions, because of the difficulty of maneuvering in ice, all tows were vertical, frequently from the sea bottom to the surface. All samples were preserved in dilute formalin.

LABORATORY PROCEDURES

In the early phases of analysis the chaetognaths were removed from the sample or from an aliquot of the sample and examined microscopically. This traditional approach to zooplankton analysis was soon abandoned, not only because it was too time-consuming, but also because many species that are sparsely distributed were not adequately represented in the aliquots. Instead of sorting, each sample was poured into a large tray 50 cm long by 20 cm wide, marked into 1,000 one-centimeter squares and examined with a binocular microscope, using transmitted light and 12 × magnification. The abundance of the various species was tabulated on hand counters or tallies until a total of 100 or more specimens of all species had been examined. For each species the percentage of the sample examined microscopically was determined by recording the number of centimeter squares examined to find the number of specimens that were counted (up to 30, occasionally more). The total number of each species in the sample was then computed on this basis. The percentage of the sample examined for each species varied from 0.1 to 100, but for most species was usually about ten per cent. After microscopic examination by the one-centimeter squares, the remainder of each sample was carefully scanned with the unaided eye to check for other recognizable species. Poorly preserved, damaged, and very small specimens were removed and examined at higher magnifications.

In the one-meter net samples nearly all specimens could be identified as to species except for badly mangled specimens and immature individuals of the *serratodentata* group. Specimens too small to be positively identified were recorded as juvenile chaetognaths.

The number of specimens of each species

in 1,000 cubic meters of water was then calculated from the amount of water filtered by the net, the percentage of the sample examined for the species, and the number of specimens found. Duplicate counts of several samples indicate that the variation between net samples due to patchiness is considerably greater than variations in the counting procedure. In order to achieve some standard method in charting species abundance, the following procedures were followed. First the total range was outlined. The limits of each species were drawn so that in general the smallest possible area of occurrence was shown. The contour intervals were made as large as possible in order to reduce the effects of patchiness and at the same time provide three or four concentration ranges. As far as possible, the same contour intervals were used for species with the same general abundance. All absences are shown on the charts.

VERTICAL DISTRIBUTION

One of the most intensive and pioneering works on the vertical distribution of zooplankton was carried out by E. L. Michael (1911) on the Chaetognatha in the San Diego region. Thomson (1947) described the vertical distribution of the chaetognaths off eastern Australia. Although data on the vertical distribution of the chaetognaths in the present material are avaialable from Transpacific Expedition, Pelagic Area Studies, and some collections in the Marine Life Research cruises, these data have not yet been studied in detail. In general, however, they confirm the work of Michael and Thomson. The only notable exceptions are found in the equatorial region, where certain mesoplanktonic and bathypelagic species are found at shallower depths than to the north and south.

All species discussed in this paper, unless otherwise stated, have their maximum abundance in the upper 100 meters of water and their lower limits at 300 to 400 meters. Because most of the net tows were from the surface to 200 to 300 meters, in the following charts of species distributions the concentrations are thought to represent the average concentration of the species in the upper 200 to 300 meters of water.

DISTRIBUTION PATTERNS IN RELATION TO THE WATER MASSES

Sagitta elegans Verrill

(Fig. 2)

The distribution of *Sagitta elegans* in the Pacific and areas to the north marks it as a northern, cold-water species. In general this species appears to be most abundant near shore. In the Arctic it decreases in concentration as the pack ice is penetrated. A section (Fig. 3) from shore into deep water, taken off Point Barrow, Alaska, in 1950 by the U.S.S. Burton Island illustrates the decrease in abundance with penetration of the pack ice. The report of Bogorov (1946) indicates that it is absent from the central region of the Arctic basin; however, his sampling was not intensive enough to prove this.

The southern boundary of *Sagitta elegans* at about 40° to 41° N. Lat. appears to agree very well with the southern limit of the Pacific Subarctic Water (Figs. 4 and 5) as shown by Sverdrup, Johnson, and Fleming (1942). The occurrence of *S. elegans* at Transpacific Station 112 (36° 35′ N. Lat., 163° 46′ E. Long.), considerably south of its usual southern limit, is accompanied by an absence of many warm-water species such as *Sagitta bedoti*, *S. pseudoserratodentata*, *S. californica*, *S. regularis*, and *S. pacifica* (Figs. 18, 12, 10, 14, and 9). Two net tows were taken at this station. The upper tow from 0 to 200 meters had no *S. elegans* but contained *S. enflata*, *Pterosagitta draco*, and *Sagitta hexaptera* (Figs. 6, 7, and 8). The presence of these widespread, warm-water species would indicate some diluted Central Water present in the upper 200 meters. The lower net tow (200–400 meters) contained *Sagitta elegans* but no species that can be considered a warm-water inhabitant. Several mesoplanktonic species such as *Sagitta* sp. (*serratodentata* group), *S. minima*, *Krohnitta subtilis*, and *Sagitta decipiens* were also present in the deeper net tow. The fauna at this station is interpreted as an isolated community that was carried considerably south of its usual range. The same phenomenon is shown at Transpacific Station 60 (44° 46′ N. Lat., 159° 55′ E. Long.), where a segment of the warm-water

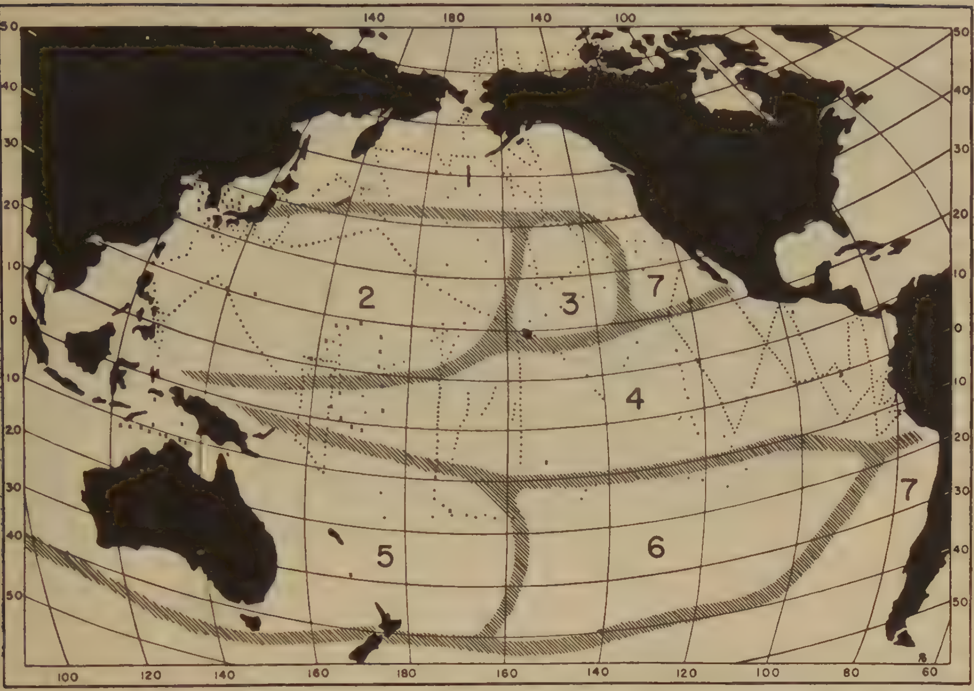

FIG. 4. Water masses of the Pacific (100–500 meters) according to Sverdrup, Johnson, and Fleming (1942). (1) Pacific Subarctic Water, (2) Western North Pacific Central Water, (3) Eastern North Pacific Central Water, (4) Pacific Equatorial Water, (5) Western South Pacific Central Water, (6) Eastern South Pacific Central Water, (7) Transition Water.

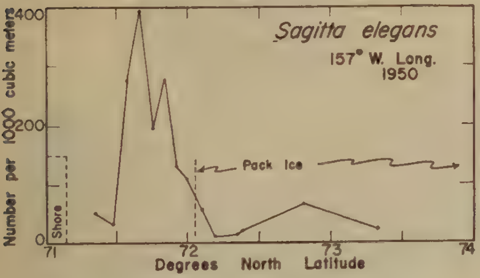

FIG. 3. Concentration of *Sagitta elegans* in the upper 100 meters of water in a section due north from Point Barrow, Alaska. Note the rapid decrease in abundance with penetration of the pack ice.

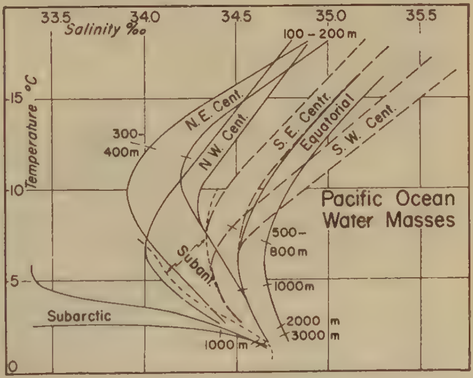

FIG. 5. Temperature-salinity relationships of the Pacific water masses below 100 meters, based on Sverdrup, Johnson, and Fleming (1942).

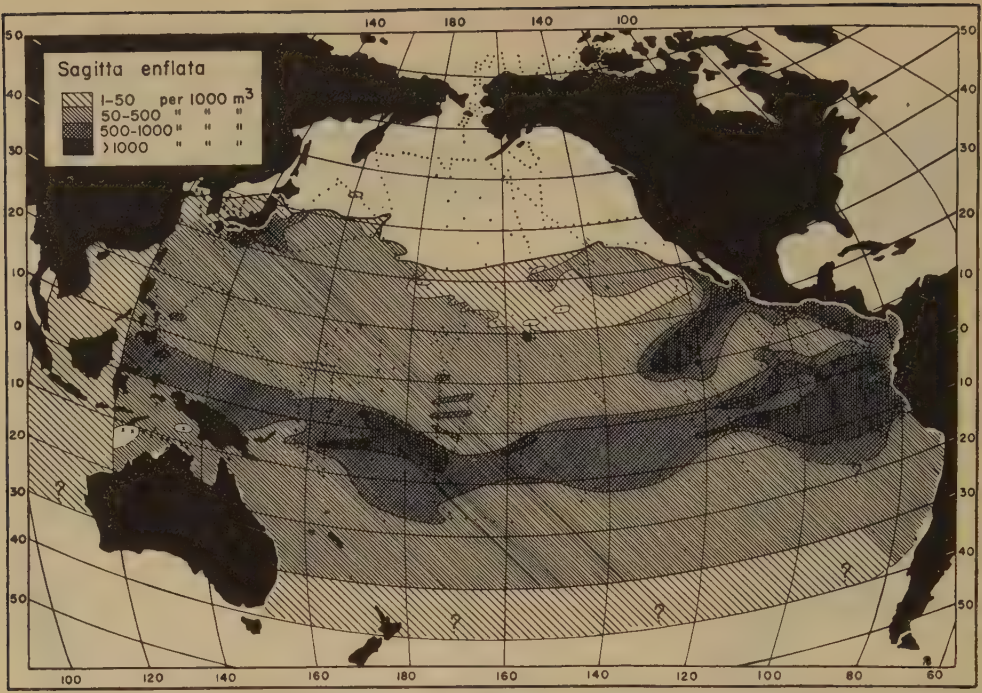
Sagitta enflata
1-50 per 1000 m3
50-500 " " "
500-1000 " " "
>1000 " " "
140
180
140
100
50
40
30
20
10
0
10
20
30
40
50
100
120
140
160
180
160
140
120
100
80
60

FIG. 6. Occurrence of *Sagitta enflata* in the Pacific. X's are stations reported by Baldasseroni (1915) and Tokioka (1940a, 1940b, 1951, 1955a, and 1956). The species was present only in the shaded area. Distribution off eastern Australia is based on Thomson (1947).

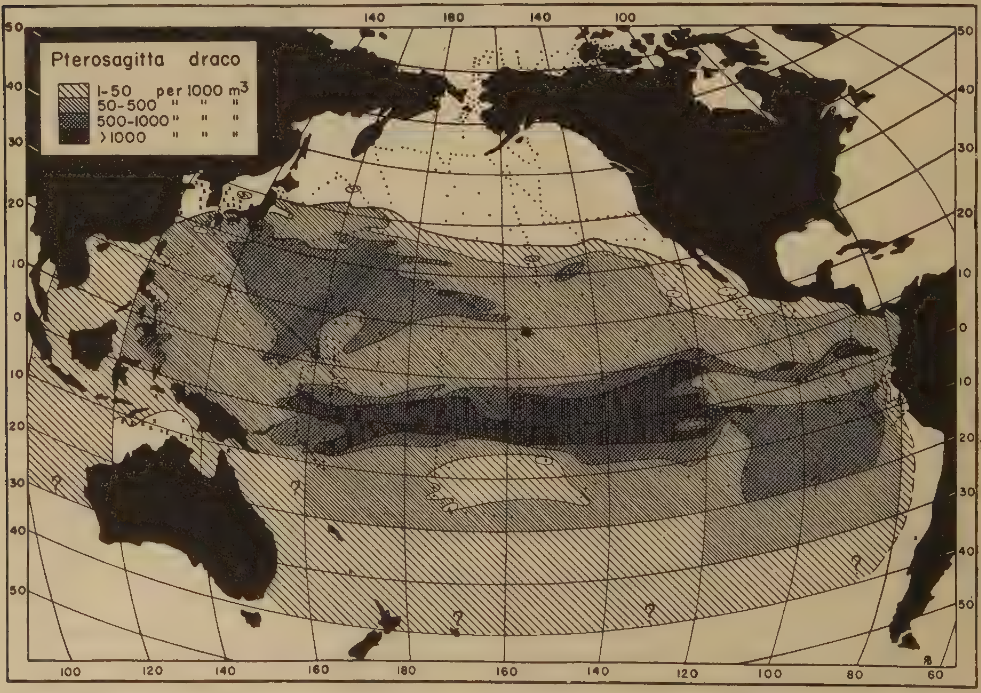
Pterosagitta draco
1-50 per 1000 m3
50-500 " " "
500-1000 " " "
>1000 " " "
140
180
140
100
50
40
30
20
10
0
10
20
30
40
50
100
120
140
160
180
160
140
120
100
80
60

FIG. 7. Occurrence of *Pterosagitta draco* in the Pacific. X's as in Figure 6. Distribution off eastern Australia is based on Thomson (1947).

(24)

fauna has been carried north of its usual range (see *S. enflata*, *Pterosagitta draco*, *Sagitta bedoti*, *S. minima*, Figs. 6, 7, 18, and 21). This expatriated community has become impoverished in number of species of chaetognaths due to some mixing with Subarctic Water (*S. elegans* was present).

Sagitta enflata Grassi

(Fig. 6)

The northern limit of another well-known chaetognath, *Sagitta enflata*, at about 40° N. Lat., approximates the southern limit of *S. elegans*. The southern limit of *S. enflata* in the Pacific has not been definitely established, but is probably in the region of 40° S. Lat. at the subtropical convergence. Baldasseroni (1915) recorded it at 35° south off Chile, and Thomson (1947) reported it as far south as 38° along the southeastern Australian coast.

Pterosagitta draco (Krohn), **Sagitta hexaptera** d'Orbigny, and **Sagitta pacifica** Tokioka (**serratodentata** group)

(Figs. 7–9)

The distributions of these three species are essentially similar to that of *Sagitta enflata*. The four occupy the Equatorial and Central Water Masses of the Pacific (Figs. 4–5). This type of distribution pattern, which can be called a cosmopolitan warm-water or widespread warm-water distribution, is very common among planktonic organisms and led Giesbrecht (1892), working on copepods, and many other workers including Ekman, in his review of marine zoogeography (1953), to divide the pelagic realm into three faunas—a warm-water fauna, and northern and southern cold-water faunas. There can be no doubt that such a division exists; however, as will be shown later, it is convenient to speak of smaller pelagic divisions as faunas rather than subfaunas, and here these three major divisions will be spoken of as provinces.

Sagitta californica Michael[3]

(Fig. 10)

The distribution of *Sagitta californica*, called *S. bipunctata* by most recent authors, is considered a special type of widespread, warm-water distribution which may be called anti-equatorial. Hubbs (1952) has suggested the term antitropical for species that avoid the tropics, including, as a special case, those that were formerly called bipolar. "Anti-equatorial" may be applied as another type of antitropicality, to the distribution of such species as *S. californica*, which reach to within five or ten degrees of the equator. The species is absent from more than 95 per cent of the stations occupied in a narrow band in the equatorial region, but occurs at more than 95 per cent of the stations on either side of this band.

Eukrohnia hamata (Möbius)

(Fig. 11)

Several species that are associated with relatively cold water show a marked increase in concentration in the band where *Sagitta californica* is extremely rare. In the San Diego region and along the coast of Baja California *Eukrohnia hamata* occurs only below 500 meters. Yet in the equatorial region shown in Figure 11 it occurs commonly above 300 meters. *E. hamata*, which is found in the upper 100 meters of the Arctic and Antarctic, shows the classic tropical submergence, but it also shows an equatorial emergence. Other examples of relatively cold water species that are more abundant in this equatorial band are *Sagitta decipiens*, *S. minima* (Fig. 21), *S. planctonis*, and *Eukrohnia fowleri*.

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[3] Although many recent authors have followed Ritter-Zahony (1911a) and used the name *Sagitta bipunctata* for an oceanic, warm-water species, this species is here called *S. californica*. The name *S. bipunctata* has been used for many species of Chaetognatha, while *S. californica*, which was very thoroughly described by Michael (1913), has been used exclusively for this oceanic species. Until the status of the name *Sagitta bipunctata* is definitely settled, it seems best to use the more precise name, *Sagitta californica*.

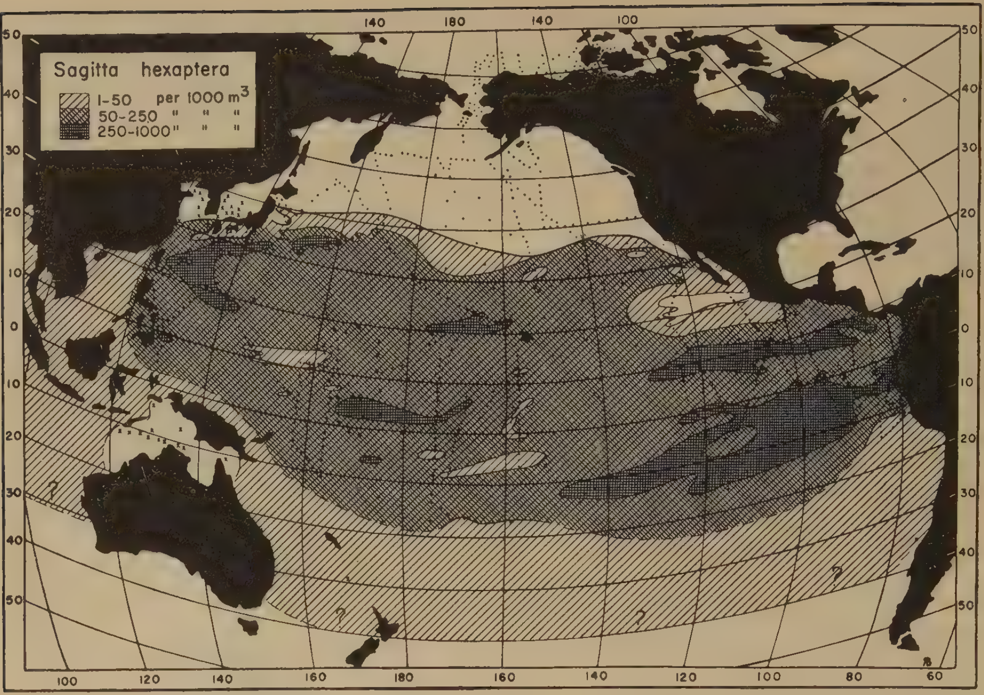
Sagitta hexaptera
1-50 per 1000 m3
50-250 " " "
250-1000" " "
140
180
140
100
50
40
30
20
10
0
10
20
30
40
50
100
120
140
160
180
160
140
120
100
80
60
?

FIG. 8. Distribution of *Sagitta hexaptera* in the Pacific. X's as in Figure 6. Distribution off eastern Australia is based on Thomson (1947).

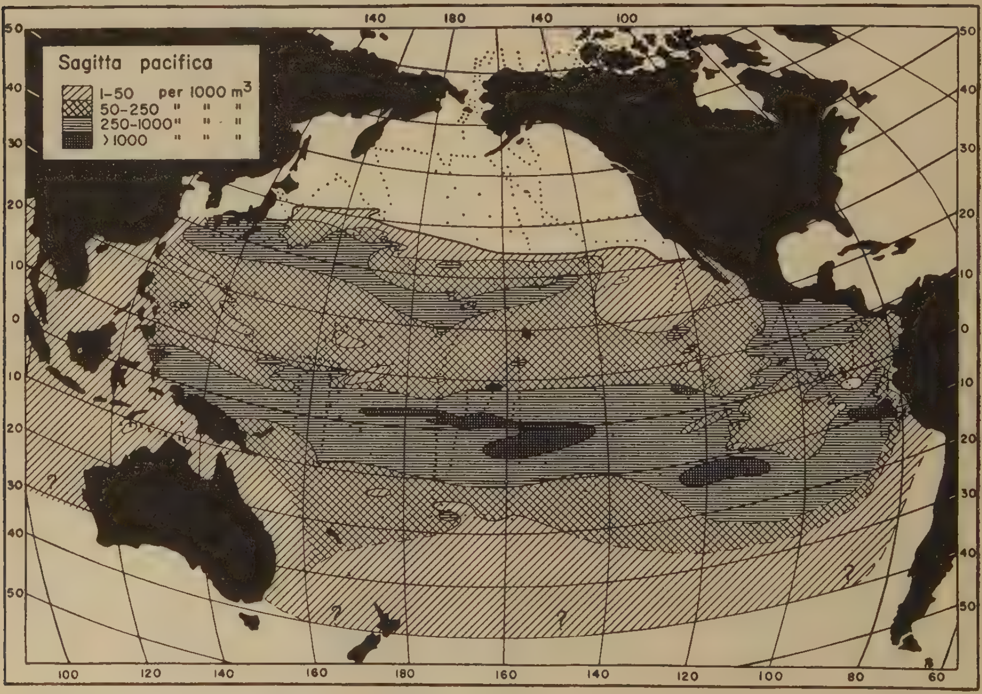
Sagitta pacifica
1-50 per 1000 m3
50-250 " " "
250-1000" " "
>1000 " " "
140
180
140
100
50
40
30
20
10
0
10
20
30
40
50
100
120
140
160
180
160
140
120
100
80
60
?

FIG. 9. Occurrence of *Sagitta pacifica* (*serratodentata* group) in the Pacific. X's are from Tokioka (1940b and 1956). Distribution off eastern Australia is based on Thomson (1947).

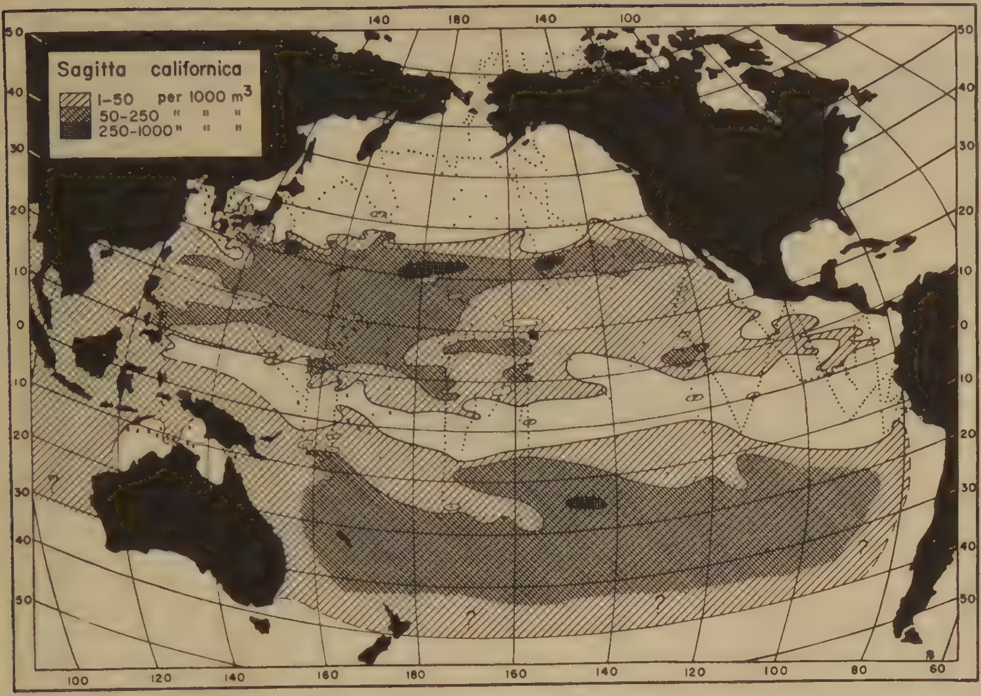
Sagitta californica
1-50 per 1000 m3
50-250 " " "
250-1000 " " "
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60
50
40
30
20
10
0
10
20
30
40
50

FIG. 10. Distribution of *Sagitta californica* in the Pacific. X's as in Figure 2. Distribution off eastern Australia is based on Thomson (1947).

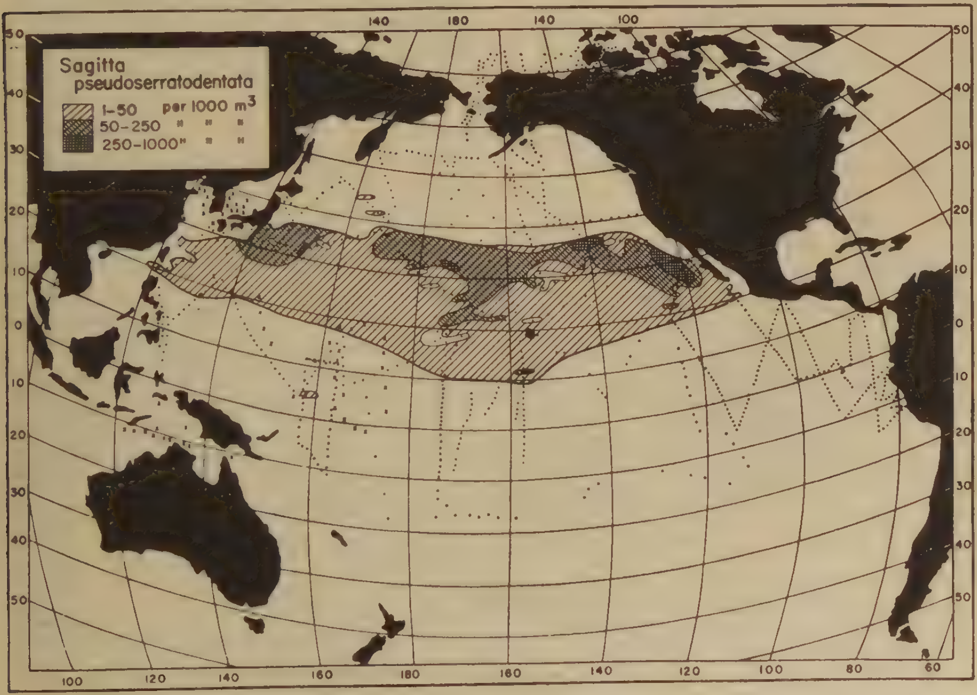
Sagitta pseudoserratodentata
1-50 per 1000 m3
50-250 " " "
250-1000 " " "
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60
50
40
30
20
10
0
10
20
30
40
50

FIG. 12. Distribution of *Sagitta pseudoserratodentata* in the Pacific. The limits of this species approximate fairly closely the limits of the Pacific Central Water (Fig. 4). X's as in Figure 2.

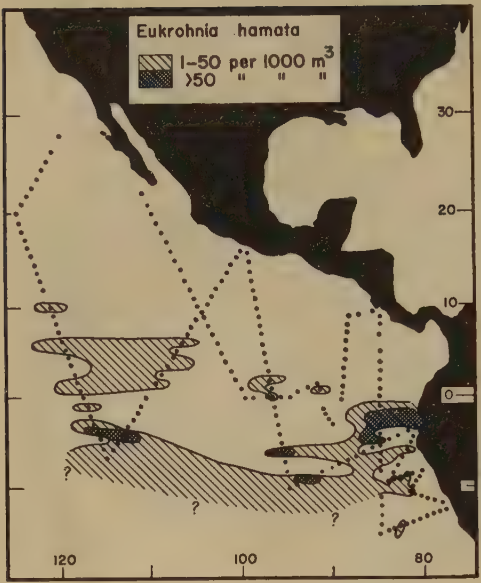

FIG. 11. Concentration of *Eukrohnia hamata* in the upper 300 meters of water in the eastern equatorial Pacific.

Sagitta pseudoserratodentata Tokioka[4]

(Fig. 12)

The Equatorial Water Mass forms a barrier that almost completely isolates the northern and southern populations of *Sagitta californica*. This Water Mass is apparently an even more formidable barrier to the southern penetration of *Sagitta pseudoserratodentata*. It is evident that the limits of this species need more extensive and intensive sampling, particularly along its southern boundary between 130° and 150° W. Long. and 140° to 160° E. Long. The boundaries are most reliably established off California and south of Hawaii, where some seasonal sampling has been carried out. The Pacific Oceanic Fisheries Investigations samples of June–August 1950, and January–March 1951, indicate a surprisingly stable boundary at 10° N. Lat., between 158° and 172° W. Long. In four crossings, the southern limit was at 10° N. Lat. three times and at 9° once. To the west of this region between 150° and 170° E. Long., the boundary is still poorly defined. Tokioka (1942, 1954b, 1955a) in discussing the chaetognaths from this western region, reported *Sagitta pseudoserratodentata* from one station (5° 3′ N. Lat., 155° 53′ E. Long.) far to the south of what appears to be its southern limit. This species roughly occupies the Central Water Masses of the North Pacific (Fig. 4), with the poorest fit in the southwest part of the Western North Pacific Central Water. It penetrates to the coast of Baja California as do the cosmopolitan warm-water species. From the standpoint of the species present, this water is more characteristic of the East Pacific Central Water than of the California Current or Transition Water as described by Sverdrup, Johnson, and Fleming (1942).

Tokioka (1954a) also reported *Sagitta pseudoserratodentata* close to the east coast of Japan. In the Transpacific and Troll Expeditions it was not found there (Fig. 12). According to Tokioka, who has carried out seasonal sampling, the distribution of the chaetognaths along the coast of Japan changes considerably with time. Over a period of 12 months he found that *S. pseudoserratodentata* formed only 1.3 per cent of the chaetognath fauna in Sagami Bay, indicating that only a very small amount of Central Water penetrates the Bay during the year. In a dense swarm of chaetognaths associated with a small red tide in the Bay, *S. pseudoserratodentata* formed only two per cent of the chaetognath fauna. Off the Southern California coast on the other hand, in the Pacific Central Water, *S. pseudoserratodentata* often makes up 20 per cent of the chaetognath fauna. It would seem that this species might be found in the South Pacific Central Water, but so far it has not been taken there. Because the distribution of this species corresponds rather closely to that of the North Pacific Central Water (Fig. 4), it is best described, zoogeographically, as a "central species"; and it is thought that *Sagitta pseudoserratodentata* is representative of a large group of species of other animal phyla

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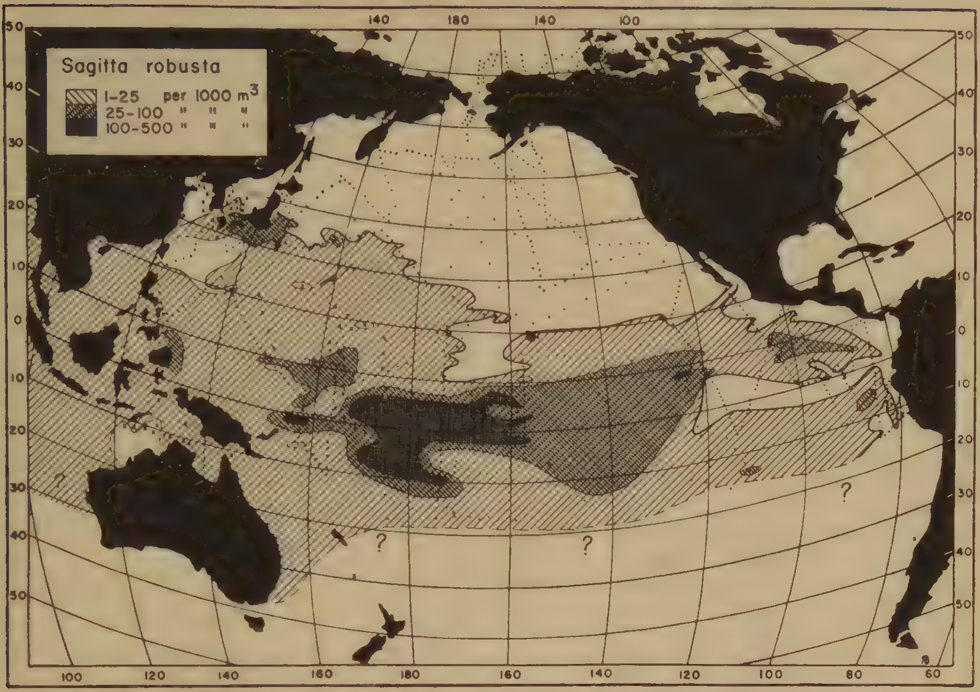
[4] A revision of the *serratodentata* group has been proposed by Furnestin (1953, 1957). Her nomenclature is partially followed, but *Sagitta pseudoserratodentata* is regarded here as a valid species (Bieri 1957).


Sagitta robusta
1-25 per 1000 m³
25-100 " " "
100-500 " " "
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60
50
40
30
20
10
0
10
20
30
40
50
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?
?

FIG. 13. Occurrence of *Sagitta robusta* in the Pacific. This species is absent from the Eastern North Pacific Central Water. X's as in Figure 6. Distribution off eastern Australia is based on Thomson (1947).

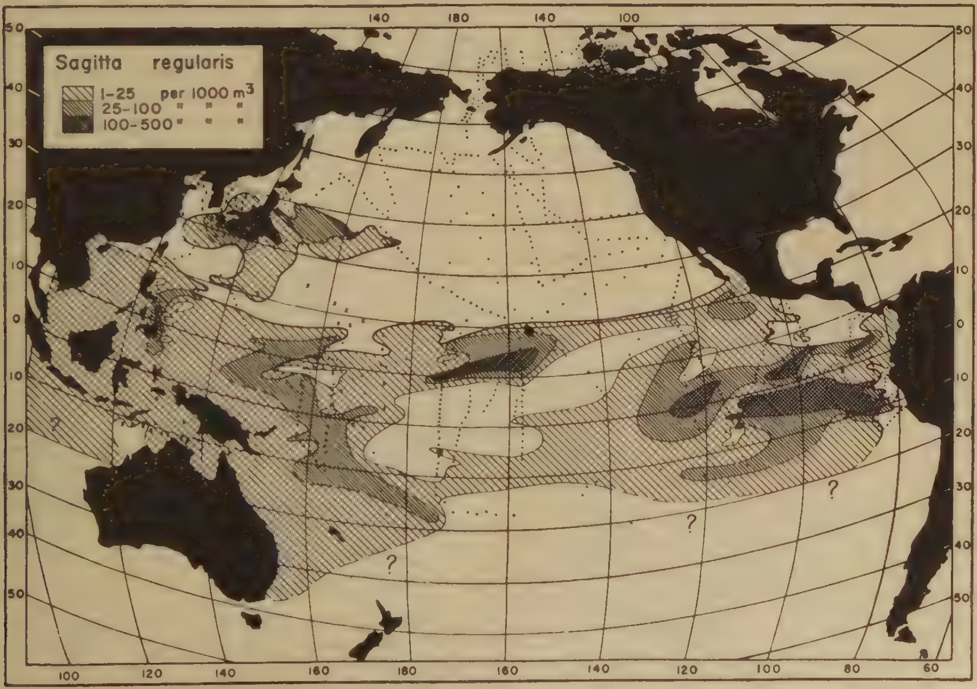
Sagitta regularis
1-25 per 1000 m³
25-100 " " "
100-500 " " "
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60
50
40
30
20
10
0
10
20
30
40
50
?
?
?
?

FIG. 14. Distribution of *Sagitta regularis* in the Pacific. The distribution of this species is similar to that of *Sagitta robusta*. X's as in Figure 2. Distribution off eastern Australia is based on Thomson (1947).

that comprise a distinctive North Pacific Central Fauna.

Sagitta robusta Doncaster

(Fig. 13)

The distribution of *Sagitta robusta* appears to be typical of a number of species of Chaetognatha. It occurs throughout most of the equatorial region and spreads into the Central Water Masses in the Western Pacific. It is absent from the Eastern North Pacific Central Water Mass. Whether or not it is absent from the Eastern South Pacific Central Water has not been established. Since this water mass is very similar to the Pacific Equatorial Water in its temperature and salinity relationships, the species might be able to penetrate this area (Figs. 4–5). In its absence from the region of the Galapagos, *S. robusta* recalls *S. californica* (Fig. 10).

Although this type of distribution can be described as tropical, it seems best to use the term equatorial-west-central, because the species occurs far to the north and south of the tropical zone in the Western Pacific.

Sagitta regularis Aida, **Krohnitta pacifica** (Aida), and **Sagitta ferox** Doncaster

(Figs. 14–16)

These species are regarded as essentially equatorial-west-central species with the extremes of their ranges similar to that of *Sagitta robusta*. However, they are more patchy in their distribution and present a rather confused picture.

Sagitta regularis, like *S. robusta*, is absent from the Eastern North Pacific Central Water (Fig. 14). Much of the area in the center of its range where it has not yet been found may be filled in by future expeditions using larger nets.

Krohnitta pacifica is absent in a band from about 5° to 15° N. Lat. almost across the Pacific (Fig. 15). Both it and *Sagitta ferox* (Fig. 16) extend slightly into the Eastern North Pacific Central Water, northeast of Hawaii, whereas *S. robusta* and *S. regularis* do not.

Sagitta friderici Ritter-Zahony, **Sagitta crassa** Tokioka, **Sagitta bedoti** Beraneck, **Sagitta neglecta** Aida, and **Sagitta pulchra** Doncaster

(Figs. 17–20)

The distributions of the preceding eleven species show varying degrees of association with the water masses. There are other species that apparently cut across water masses or have limits which do not correspond with the water masses. These species can be divided into three major groups. First there is a group of species that live primarily in the upper 200 meters, which because they are most abundant near shore can be characterized as neritic or nearshore, although they may actually extend hundreds of miles out to sea. *Sagitta friderici*, *Sagitta crassa*, *S. bedoti*, *S. neglecta*, and *S. pulchra* are examples. Because it is very abundant near shore, *S. elegans* could be placed in this group, even though it appears to extend across the Pacific at 40° N. Lat.

The dependence of various species of Chaetognatha on "nearshore water" has been noted by several authors. Several explanations for this phenomenon have been advanced, each with some points in its favor. These arguments are too lengthy to be presented here in detail. It can be said, however, that there are four chief explanations: (1) unknown dissolved substance in the water, (2) static temperature-salinity relationships, (3) dynamic temperature-salinity relationships, and (4) biologic restriction through competition. The distribution of *Sagitta friderici* off California, Peru and Chile, and North and South Africa, is correlated with upwelling and suggests that temperature and salinity are related to the distribution pattern of this species. Michael (1911) has shown that off California this species, which he called *S. bipunctata*[5], migrates toward the surface at night and is most abundant during the day at about 60 meters. This is the average depth of the thermocline in that region. Although *S. friderici* may be able to stay above the thermocline, the fact that it is

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[5] Based on an examination by the author of 280 vials containing chaetognaths identified by E. L. Michael.

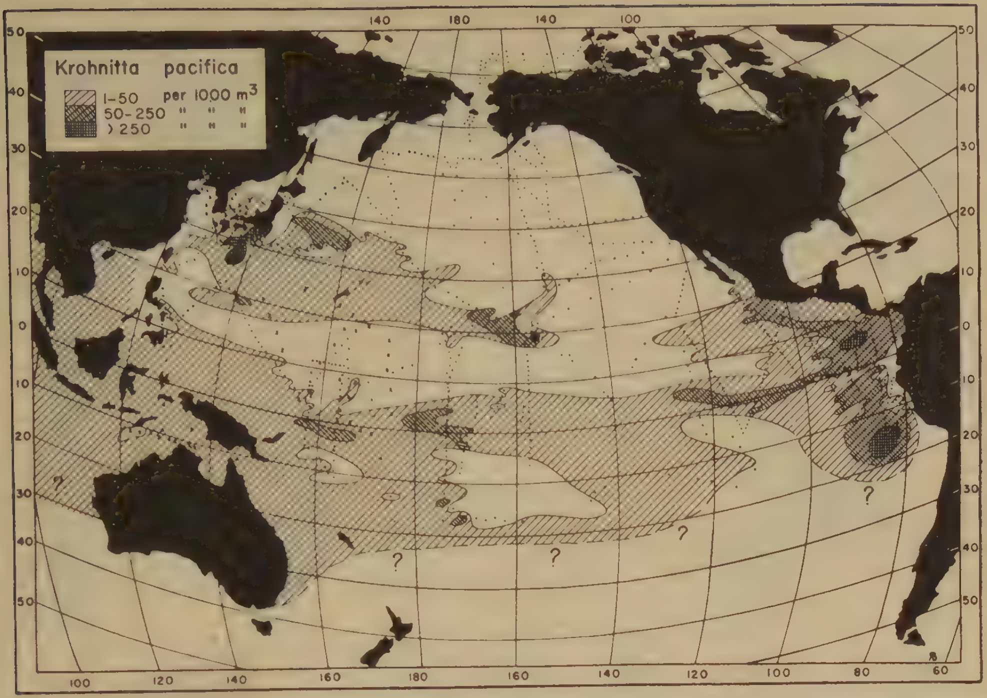
Krohnitta pacifica
1-50 per 1000 m3
50-250 " " "
> 250 " " "
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60
50
40
30
20
10
0
10
20
30
40
50
?

Fig. 15. Occurrence of *Krohnitta pacifica* in the Pacific. Note that it extends slightly into the Eastern North Pacific Central Water northeast of Hawaii. X's as in Figure 2. Distribution off eastern Australia is based on Thomson (1947).

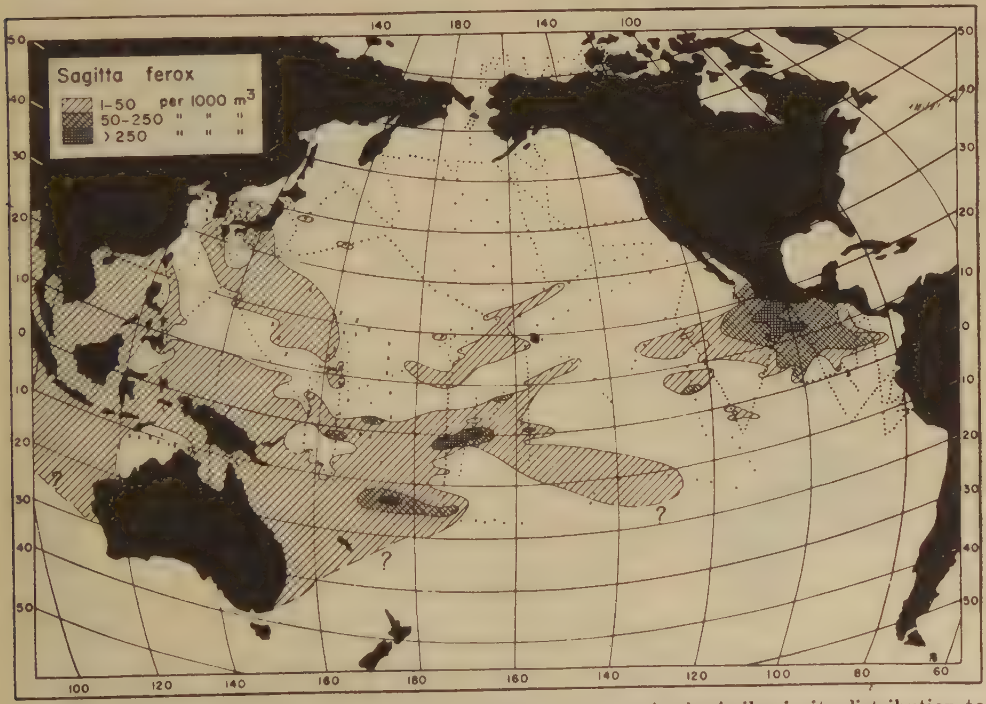
Sagitta ferox
1-50 per 1000 m3
50-250 " " "
> 250 " " "
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60
50
40
30
20
10
0
10
20
30
40
50
?

Fig. 16. Distribution of *Sagitta ferox* in the Pacific. This species is similar in its distribution to *Krohnitta pacifica*. X's as in Figure 2. Distribution off eastern Australia is based on Thomson (1947).

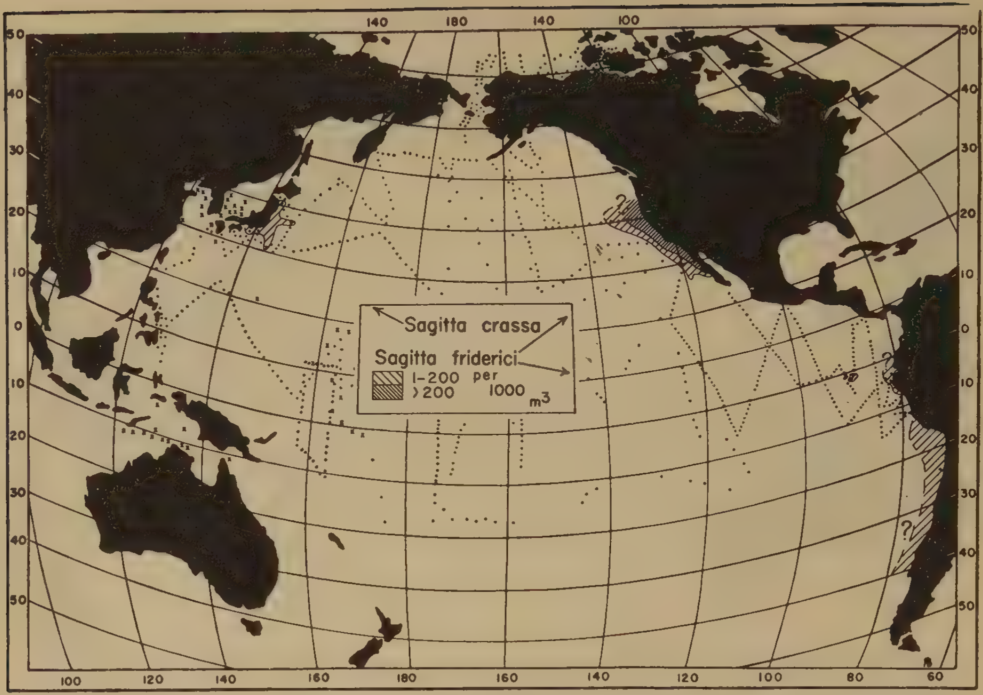
Sagitta crassa
Sagitta friderici
1-200 per 1000 m^3
>200
?
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60

FIG. 17. Known extent of the two *Sagitta friderici* populations in the Pacific. This species dominates the California and Peru Currents. *Sagitta crassa* off Japan is a closely related species. X's as in Figure 2.

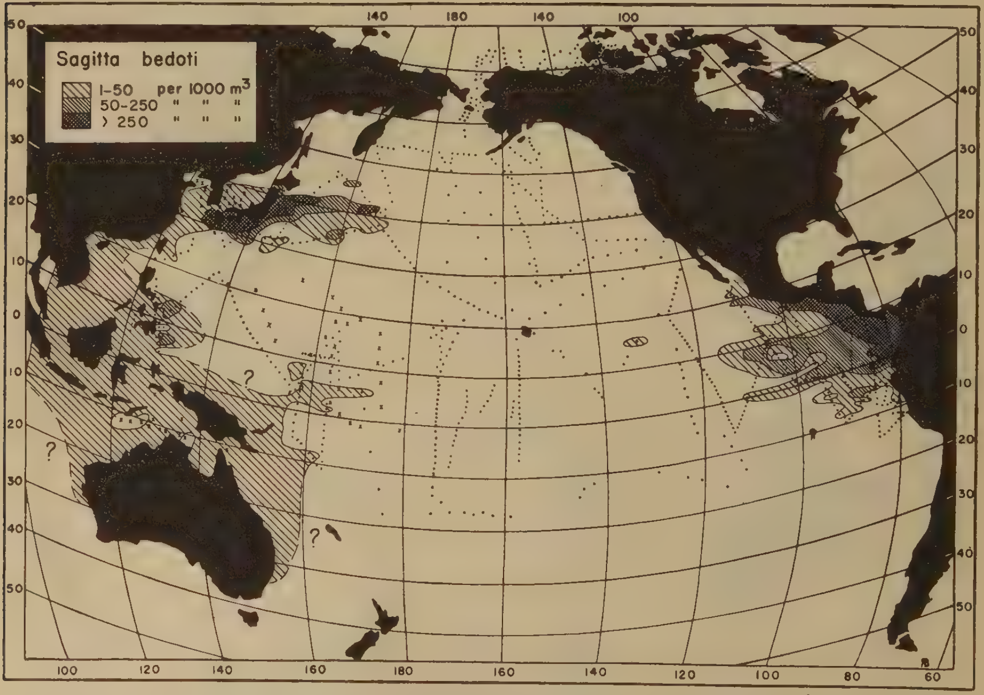
Sagitta bedoti
1-50 per 1000 m^3
50-250 " " "
> 250 " " "
?
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60

FIG. 18. Known extent of the two *Sagitta bedoti* populations in the Pacific. The distribution of this species is reminiscent of the equatorial-west-central species such as *Sagitta robusta*, but it is apparently unable to cross the oceanic equatorial region. X's as in Figure 2. Distribution off eastern Australia is based on Thomson (1947).

(32)

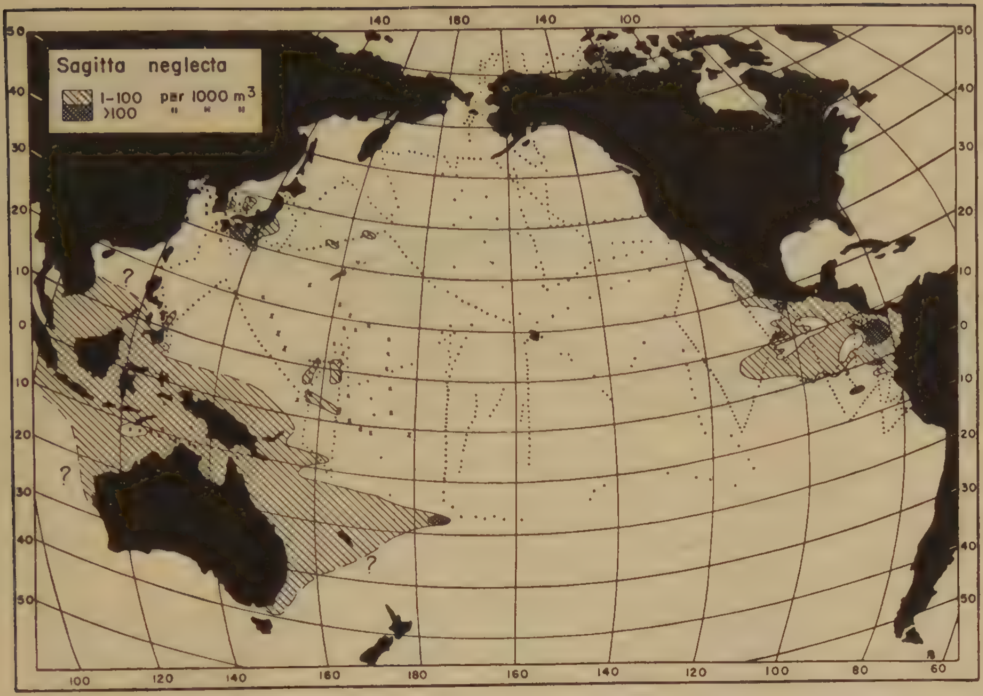
Sagitta neglecta
1-100 per 1000 m3
>100 " " "
?
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60
50
40
30
20
10
0

FIG. 19. Known extent of *Sagitta neglecta* in the Pacific. It has essentially the same distribution as *Sagitta bedoti*, but is not so abundant as that species. X's as in Figure 2. Distribution off eastern Australia is based on Thomson (1947).

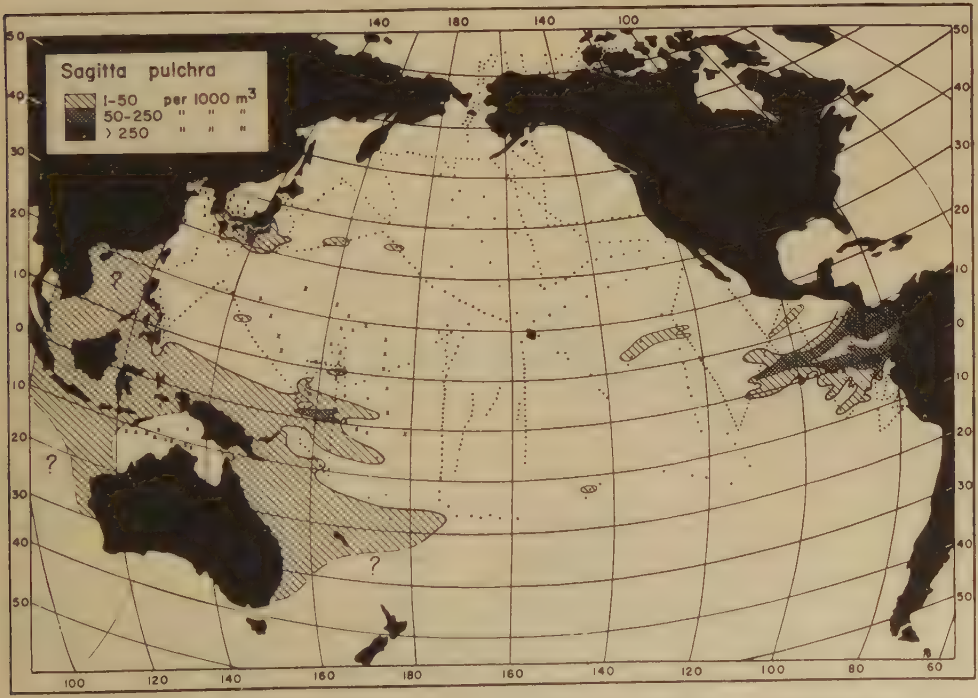
Sagitta pulchra
1-50 per 1000 m3
50-250 " " "
> 250 " " "
?
140
180
140
100
100
120
140
160
180
160
140
120
100
80
60
50
40
30
20
10
0

FIG. 20. Known extent of *Sagitta pulchra* in the Pacific. It is similar in its distribution to *Sagitta bedoti* and *S. neglecta*. X's as in Figure 2. Distribution off eastern Australia is based on Thomson (1947).

often taken at depths down to 200 meters indicates that it is able to withstand rapid and pronounced temperature changes. It can be postulated that the oceanic species cannot withstand the temperature and salinity variations of the neritic region, and that *Sagitta friderici* cannot withstand the warmer oceanic waters to the west and south or the cold waters to the north of its range. Whether or not the distributions of the disjunct equatorial species (*Sagitta neglecta*, *S. pulchra*, and *S. bedoti*) can be accounted for by similar phenomena remains to be seen.

Sagitta minima Grassi and **Sagitta** sp. (**serratodentata** group)

(Figs. 21–22)

A second group of species that show poor agreement with the water masses live primarily between 100 and 300 meters. These are the mesoplanktonic species. In certain regions of reduced surface temperature these forms may be very abundant in the upper 100 meters. Typical of this group are *Sagitta minima* and *Sagitta* sp. (*serratodentata* group, possibly *S. serratodentata tasmanica* Thomson 1947).

Sagitta minima (Fig. 21) seems to inhabit the regions between water masses or the regions of mixing of the water masses. A few individuals are able to submerge under the edges of the warmer Eastern Pacific Central Water off the California Coast. Pierce (1953) has shown that in the western North Atlantic *S. minima* is most common in mixed water over the continental shelf.

Sagitta sp. (Fig. 22) shows a marked morphologic change in the region of 20° N. Lat., in apparent association with the faunal boundary there. It is possible that subspecies should be erected for the two populations, or they may actually be two separate species. If so, the two populations would be similar in distribution to *Sagitta friderici* and *S. bedoti* (Figs. 17–18), which are closely related. It seems likely that the extension of *Sagitta* sp. north into the California Current from the Pacific Equatorial Water is related to the Equatorial Water beneath the California Current at depths of 200 to 800 meters. Michael (1911) has shown that this species is most common off San Diego at 200 to 300 meters depth.

Sagitta decipiens Fowler, **Sagitta lyra** Krohn, **Krohnitta subtilis** (Grassi), and **Sagitta maxima** Conant

Although these species appear to belong to the second group, they were not adequately sampled on many of the expeditions listed in Table 1, either because of the small nets used or because the tows were not deep enough. Their distribution in the samples is so patchy that it is difficult to draw any conclusions from the data at hand. The northern boundary of *Sagitta minima* at 42° to 45° N. Lat. also seems to be the northern limit for *S. decipiens*, *Krohnitta subtilis*, and *Sagitta lyra*, and the southern limit of *S. maxima*.

Sagitta macrocephala Fowler, **Sagitta planctonis** Steinhaus[6], and **Eukrohnia fowleri** Ritter-Zahony

These three bathypelagic species, comprising a third group, occur chiefly below 500 meters throughout the Pacific as far north as 55°. As was previously mentioned, *Eukrohnia hamata* extends from the Arctic to the Antarctic and varies its depth from the surface to below 500 meters. *Sagitta planctonis* and *Eukrohnia hamata* are frequently found in the upper 300 meters of water in the Equatorial Water Mass.

Heterokrohnia mirabilis Ritter-Zahony

The abyssal-pelagic chaetognath, *Heterokrohnia mirabilis*, has been reported from the Antarctic, and recently from Kamchatka (Tchindonova 1955). It occurred in only one of the 3,000 samples discussed here, Shellback trawl no. 14 (from 11° 2′ N. Lat., 91° 46′ W. Long. to 11° 55′ N. Lat., 91° 32′ W. Long.) in a deep tow to 2,300 meters. This record shows that *H. mirabilis* is not a bipolar species as postulated by Tchindonova (1955), but is probably a cosmopolitan very deep water species.

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[6] David (1956) recently revised the *Sagitta planctonis* group. In the present work all specimens of this group are provisionally considered one species, here called *S. planctonis*.

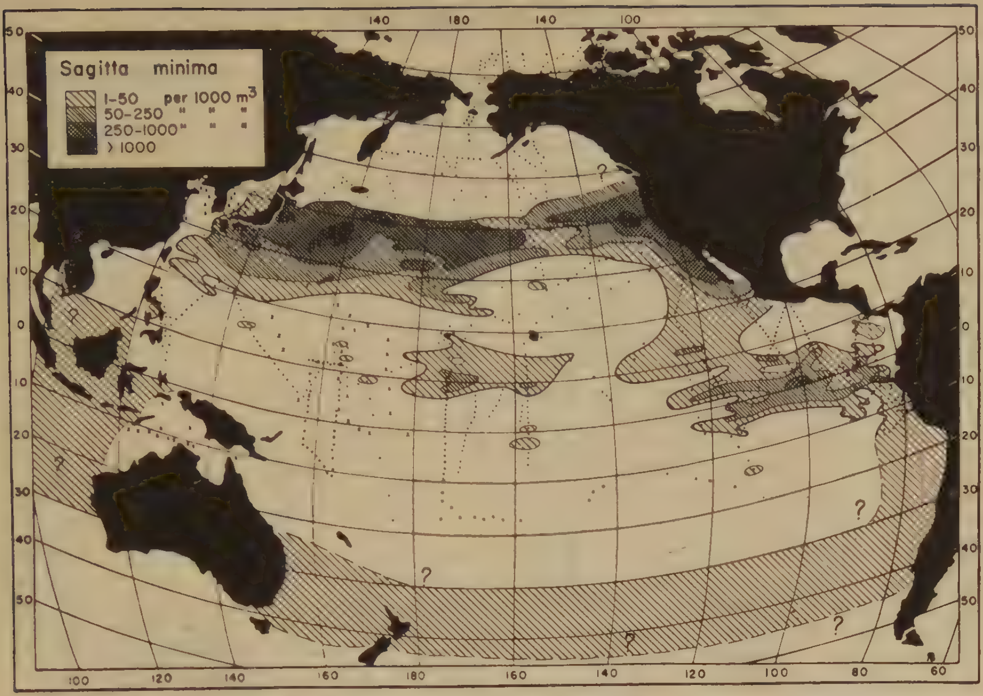
Sagitta minima
1-50 per 1000 m³
50-250 " " "
250-1000" " "
> 1000

FIG. 21. Distribution of *Sagitta minima* in the Pacific. This species is most common in the regions of mixing of water masses. X's as in Figure 2. Distribution off eastern Australia is based on Thomson (1947).

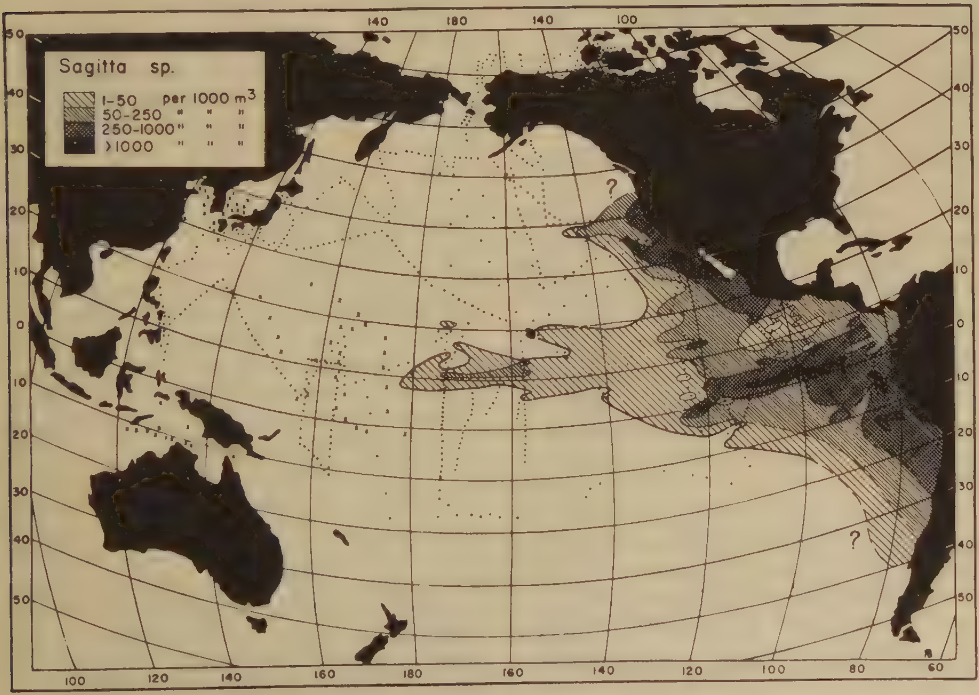
Sagitta sp.
1-50 per 1000 m³
50-250 " " "
250-1000" " "
>1000 " " "

FIG. 22. Distribution of *Sagitta* sp. (*serratodentata* group) in the Pacific. X's as in Figure 2.

NATURE OF THE BOUNDARY REGIONS

The major part of plankton indicator work is concerned with changes in the geographic limits or boundaries of species and to a lesser extent with changes in relative proportions of various species and changes in the extent of the nursery grounds of species. In a study such as the present one, which encompasses as large an area as the Pacific, a comprehensive study of the boundaries can not be presented. Instead, a few of the techniques which may throw more light on this type of problem are pointed out.

In only a few places have the species boundaries been crossed frequently enough or at sufficiently close spatial intervals to permit even a preliminary analysis of seasonal changes and mixing processes in the boundary regions. The limit of *Sagitta pseudoserratodentata* south of Hawaii was traversed four times, twice in summer and twice in winter. On three of these traverses the southern limit was at 10° N. Lat., and on the fourth traverse it was at 9° N. Lat. There are only slight differences in the patterns of abundance as measured by running averages by two's (Fig. 23) between the lines at 172° and 158° W. Long.

Vertical profiles of temperature and salinity across this boundary at 172° W. Long. are shown in Figure 24. A layer of warm water between 12° N. Lat. and 3° N. Lat. and a dome of relatively cold water below are conspicuous features of the region. If it is postulated that *Sagitta pseudoserratodentata* can live only between temperatures of 18 and 26.5° C., then it would be confined to a narrow band of water 50 meters thick at 9° N. Lat. If this temperature range were responsible for its distribution, the species should reappear in good numbers south of 3° N. Lat. Its absence from this region may be due to the higher salinities in the upper 150 meters of water south of 6° N. Lat.

The concentration gradients, estimated from Figure 23 by eye and expressed as change per degree of latitude, vary from 4 to 5, the gradient decreasing irregularly but gradually from 20° N. Lat. On the other hand, the limit of the same species southwest of Baja California at 120° W. Long., on two crossings, had concentration gradients of 15 and 25 (Fig. 23). These compare with a concentration gradient of approximately 80 for *Sagitta elegans* north of Point Barrow (Fig. 3).

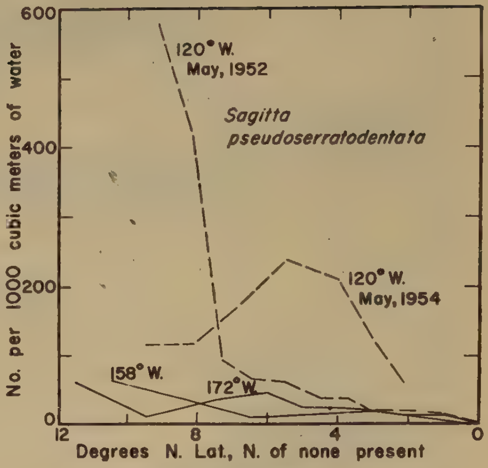

FIG. 23. Decrease in concentration of *Sagitta pseudoserratodentata* as the southern limit of its range is approached. The gradients at 158° and 172° W. Long. are about five specimens per 1,000 cubic meters of water per degree of latitude. At 120° W. Long. the gradients are of the order of 15 and 25. The sections at 158° and 172° W. Long. were made in June to August, 1950. Sections at 158° and 172° made in January to March, 1951, were about the same as those made in June to August, 1950.

The concentration gradient can be used as a measure of the abruptness of the species limit and is greatest where a species is limited by a land mass. Off San Diego, for example, concentration gradients of *Sagitta friderici* near shore are frequently as high as 5000 in 60 nautical miles. The few comparisons that have been made indicate that changes in the gradients with time are less pronounced than are the differences due to geographic location.

Another measure of the strength of a boundary is the number of species that are limited by the boundary. In this respect the boundary southwest of Baja California is one of the most striking yet found in the Pacific. At least eight species of chaetognaths (*Sagitta pseudoserratodentata*, *S. robusta*, *S. ferox*, *S. pulchra*, *S. bedoti*, *S. neglecta*, *S. regularis*, and *Krohnitta pacifica*),

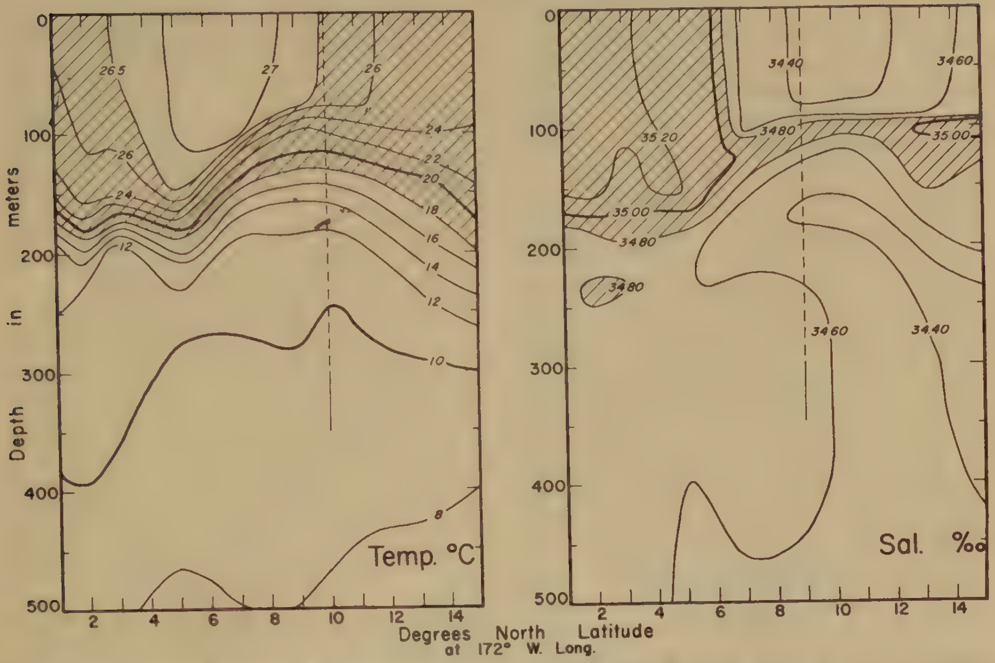

Fig. 24. Vertical sections of temperature and salinity at 172° W. Long. (Fig. 1). The southern limit of *Sagitta pseudoserratodentata* at 10° N. Lat. is indicated by dashed lines.

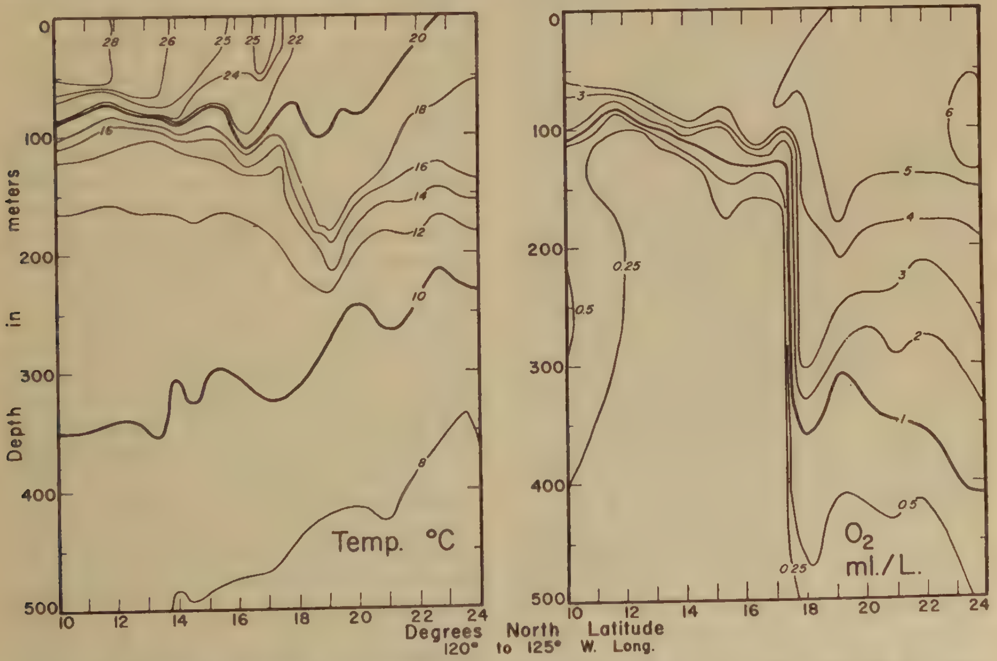

Fig. 25. Vertical sections of temperature and dissolved oxygen between 120° and 125° W. Long. (Fig. 1). The sharp gradients in temperature and especially oxygen at 18° N. Lat. are conspicuous.

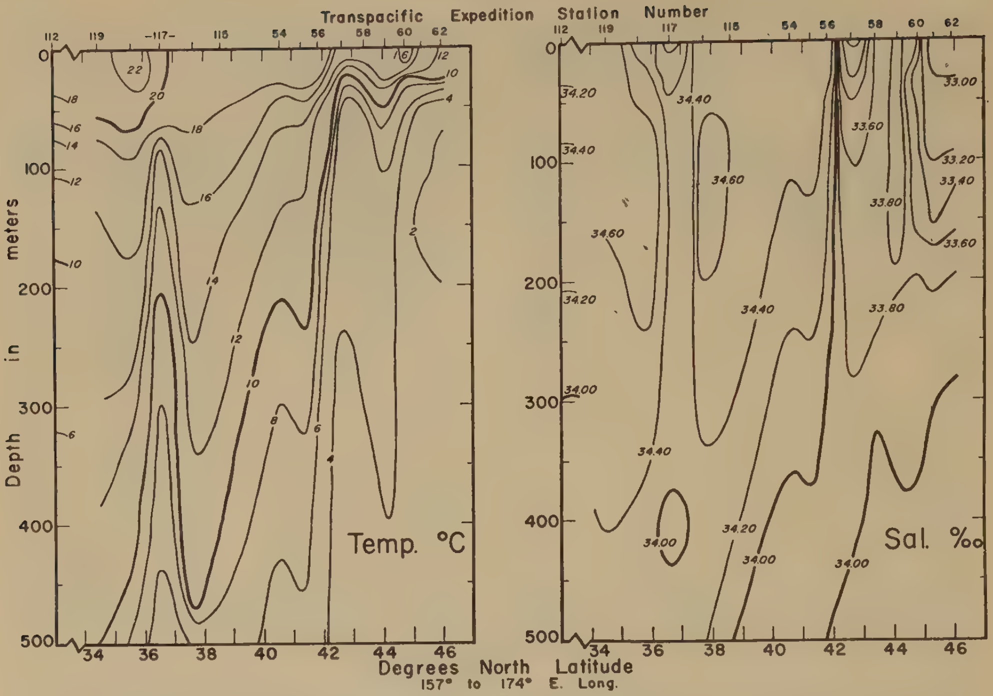

FIG. 26. Vertical sections of temperature and salinity in a section northeast of Japan (Fig. 1). Not the small pool of 16° C water in the upper 15 meters at 45° N. Lat.

one-third of those occurring in the region, have either a northern or southern limit there. This boundary is marked by a sharp temperature change at the surface between 17° and 18° N. Lat. as shown by the four isotherms (22–25°C.) that reach the surface there (Fig. 25). This temperature "wall" extends to a depth of at least 200 meters. The corresponding vertical section of oxygen concentration shows that there is a pronounced boundary extending at least as deep as 500 meters with very little mixing across the boundary. The oblique net tows available from Shellback Expedition when these sections were made, do not throw any light on the question of the relative importance of temperature, salinity, and oxygen in this boundary region.

The transport of expatriated communities across the subarctic barrier, presumably by large eddies, was discussed above. Vertical sections of temperature and salinity between Transpacific Expedition stations 62 to 54 and 115 to 119 illustrating this phenomenon are shown in Figure 26. The major feature of the region is the sharp slope of the isotherms and isohalines extending to more than 500 meters and separating cold, low salinity water to the north from warm, relatively high salinity water to the south. Station 60 (44° 46′ N. Lat., 159° 55′ E. Long.) has a thin layer of comparatively warm water in the upper 15 meters, and this is presumed to be the source of the warm water species taken at this station.

Station 112 (36° 35′ N. Lat., 163° 46′ E. Long.) had *Sagitta elegans* present in a tow from 160 to 280 meters deep. The T-S diagram from this station indicates that only Pacific Central Water was present in this depth range. *Sagitta elegans* may have persisted in this water until it lost all of its subarctic character. It is also possible that the net tow sampled water with temperature-salinity characteristics different from that sampled by the hydrographic cast since the two observations were not simultaneous.

With the development of a technique for microscopically examining zooplankton at sea (Bieri 1956), it is now possible to sample selected boundaries at very close intervals of time and space. A synoptic approach should lead to a better understanding of the mechanisms that tend to mix separated populations and permit detailed studies of population structures in the different boundary regions.

COMPARISON WITH THE DISTRIBUTION OF OTHER PLANKTON ORGANISMS

Although it has long been known that there are characteristic plankton communities in the sea, these communities have been worked out in only a few restricted regions, chiefly parts of the North Atlantic. In attempting to determine the primary cause or causes of the species limits, it is important to compare the distributions of the chaetognaths with those of other zooplankton organisms, especially those with a different mode of nutrition, and to phytoplankters which in addition to different nutritional requirements have a vastly different method of reproduction and rate of growth. If the species barriers or limits are in general the same for many different groups of organisms, then any explanation of the cause of the species limits must explain not only those for the chaetognaths, but also those for the other animal and plant groups. Although the distribution of each species of chaetognath is unique in itself, certain similarities between various species have been pointed out in the discussion of distribution patterns. These general types of distribution are similar to the distribution of other animal species.

Most previous observations in the Pacific have been so scattered and far apart that it is difficult to establish the range or limit of any species. However, where sampling has been detailed, the other zooplankton groups coincide fairly well with the distributions of the chaetognath species. For example, Bowman (1955) described a new species, *Calanus lighti*, which has a distribution off California and Baja California that is typical of the cosmopolitan warm-water species. However, *C. lighti* is absent from the eastern equatorial Pacific and is apparently a central species similar in distribution to *Sagitta pseudoserratodentata*.

Boden, Johnson, and Brinton (1955) delimit the generalized distributions of the Pacific euphausiids. *Nyctiphanes simplex*, near shore in the California and Peru Currents, is similar in distribution to *Sagitta friderici*. The range of *Euphausia recurva* is split into a north and south central population, similar to, but more pronounced than the anti-equatorial distribution of *Sagitta californica*. *Euphausia tenera* is an equatorial-west-central species similar to *Sagitta robusta*. *Euphausia hemigibba* is largely restricted to the North Pacific Central Water (*Sagitta pseudoserratodentata*), while *Euphausia gibba* is restricted to the South Pacific Central Water.

In their study of the very extensive Carnegie material, Graham and Bronikovsky (1944) charted the occurrences of 52 species of the genus *Ceratium* and thus provided comparative material. On the basis of these species distributions, the Pacific and Atlantic were each divided into a cold and warm region at about 40° N. Lat., similar to what has been shown in this paper for the chaetognaths. Off the coast of South America the authors established a southeast Pacific region that appears to be a delineation of the Eastern South Pacific Central Water. Many of the *Ceratium* species appear to be similar to the Chaetognatha in distribution.

Their Chart 2 (Graham and Bronikovsky 1944, p. 187) for *Ceratium cephalotum* shows a distribution similar to that of *Sagitta californica* and *Euphausia recurva*, occupying the North and South Central Water, but apparently excluded from the Peru and California Currents and the Equatorial Water Mass. *Ceratium belone* also seems to have an anti-equatorial or perhaps wider antitropical distribution. *Ceratium gravidum*, *C. candelabrum*, *C. pulchellum*, *C. semipulchellum*, *C. massiliense*, *C. contorticum*, and at least seven or eight other species of the genus are widespread, warm-water species similar to *Sagitta enflata*. *Ceratium filicorne* appears to be restricted to the Pacific Central Water. *C. deflexum* is an equatorial-west-central species absent from the Eastern North Pacific Central Water, as is *C. lunula*. Graham and Bronikovsky suggest that, "It is possible

(39)

that the slight variations in salinity found in the oceanic waters have no influence on the distribution of *Ceratium* species." They point out that the limit of the warm and cold water provinces in the Atlantic is at a surface salinity of about 36‰, whereas in the Pacific the same species are limited at a surface salinity of 33 to 34‰. On the other hand, the correlation with temperature is rather poor. The distribution of *C. lunula* (their Chart 31, p. 197) shows poor agreement with surface temperature. However, the limits of this species do agree quite well with the extent of the water masses as defined by temperature and salinity combined. *Ceratium tripos atlanticum* may be similar in distribution to *Sagitta friderici*. The eastern neritic temperate species such as *Sagitta friderici*, *Nyctiphanes simplex*, and *Ceratium tripos atlanticum* are associated with upwelling water in the Peru and California Currents and give these currents unique faunas.

As was pointed out in the discussion of the distribution of *Sagitta robusta*, the Eastern South Pacific Central Water is very similar to the Equatorial Water in its temperature and salinity relationships. It is interesting that Graham and Bronikovsky's data show three equatorial-west-central species—*Ceratium breve*, *C. incisum*, and *C. lunula*—that are absent from the Eastern South Pacific Central Water, and three other equatorial-west-central species—*C. deflexum*, *C. reflexum*, and *C. falcatum*—that occur in the Eastern South Pacific Central Water.

DISCUSSION

Each of the upper water masses of the Pacific has a unique temperature-salinity regimen that is brought about in large part by the oceanic currents. For example, large horizontal current gyres in the Subarctic and Central Water Masses tend to maintain the relatively small range of temperature-salinity values found in these waters. The oceanic circulation, which allows some lateral mixing between the water masses as shown by the temperature-salinity relationships, also tends to keep various animal populations isolated from one another. On the other hand, the upper water masses are defined on the basis of the temperature-salinity relationships found below 100 meters, because comparatively large seasonal changes and other variations in temperature and salinity confuse the interpretation of lateral mixing in the surface layers.

In the preceding presentation the apparently close relationship of species limits to water mass boundaries has been emphasized. Although the postulated relationship may be spurious, there are three possibilities which may justify such comparisons even though it is apparent that most of the species discussed have their greatest abundance in the upper 100 meters.

First, even though the majority of the species are most abundant above 100 meters, all of them extend at least as deep as 200 meters, and many of the warm water species such as *Sagitta enflata* have been reported from as deep as 500 meters. Thus it is possible that as a population approaches a boundary region, the surface-living individuals are eliminated first and the deeper-living individuals would then define the total range.

Secondly, the upper-living (epiplanktonic) species are capable of some submergence when unfavorable conditions are encountered in the surface layers. Although this is especially true when a species encounters water warmer than it can tolerate, in some regions relatively high salinity, high temperature water may be carried beneath colder, less saline surface waters. In such localities and where submergence is possible the T-S relationships of the water masses would reflect the environment of the species limits.

Finally, the fact that there appears to be good agreement between species limits and water-mass boundaries would indicate that the temperature-salinity relationships below 100 meters, which define a water mass throughout the greater part of its extent, also occur at the surface in the boundary regions. This is known to be the case in certain regions where the water masses are formed, as for example northeast of Japan where the Oyashio and Kuroshio Currents meet and give rise to the Intermediate and North Pacific Central Water Masses. Al-

(40)

though extensive studies of seasonal temperature variations in the upper 100 meters of water have been made in recent years following the advent of the bathythermograph, seasonal studies of temperature and salinity together on a broad scale are not yet available. The detailed examination of these possibilities by future expeditions will either confirm or negate the implied causal relationship between species limits and temperature-salinity.

Knowing the distributions that have been presented, it is possible, on the basis of the chaetognath species present, to locate quite closely the locality from which a plankton sample has been taken, provided that the tow is oblique from the surface to 300 meters, and the net large enough to take a sufficiently large and reliable sample. For example, the presence of *Sagitta elegans* would place a sample north of 40 degrees, or, if *S. decipiens* were absent, north of 45 degrees. The North Pacific Central Water can be distinguished by the presence of *Sagitta pseudoserratodentata*. The absence of *S. robusta* and *S. regularis*, with *S. pseudoserratodentata* present, would show that the sample came from the Eastern North Pacific Central Water. The absence of *S. pulchra*, *S. neglecta*, *S. bedoti*, and *S. pseudoserratodentata*, with *S. robusta*, *S. regularis*, and *Krohnitta pacifica* present, would place the sample in the oceanic region of the Equatorial Water Mass. The presence of *Sagitta pulchra*, *S. bedoti*, and *S. neglecta* would place the sample in the east or west "neritic" Equatorial Water, while the presence of *Sagitta* sp. would show that the sample came from the eastern "neritic" Equatorial Water. The presence of *S. friderici* would place a sample off the coast of North or South America. Although the ability to predict the location from which a sample has been taken may have no oceanographic or practical application, it does give an indication of the relative state of knowledge of the animal group.

It is thus apparent that every region of the Pacific has a distinctive chaetognath fauna, though the chaetognaths in any local fauna are but small parts of large, widespread populations. In some regions the species composition may change very little with time. On the other hand, qualitative changes may occur quite rapidly when a locality has a species boundary through it. In certain regions, as off the coast of Baja California, the species may come from two or three different faunas with only one or two species endemic to the locality. In such places a change in the total zooplankton population can only be predicted by knowing the relative importance of the contribution of each fauna.

The North Pacific Subarctic Convergence has been recently discussed by many Japanese and Russian investigators, for instance Brodskii (1952, 1955), Bogorov and Vinogradov (1955). The Convergence separates the Subarctic and Central Water Masses at 40° to 45° N. Lat., and is the region of a major barrier for the phytoplankton as well as the zooplankton. It is regarded as a division between two of the three great provinces of the Pacific, the northern cold-water province, and the warm-water province. Nevertheless, it is not a sharp boundary in that many of the warm-water species disappear short of the convergence, and many others do not disappear until they have been carried several degrees beyond the convergence. This is particularly true of the deeper-living species. The effectiveness of the subtropical convergence and the subarctic convergence in the Atlantic in limiting pelagic species is well established, and it seems highly probable that the Pacific subtropical convergence at about 40° S. Lat. will be shown to be an equally formidable barrier to many species of Chaetognatha.

The agreement between the species distributions and the water masses is best in the Eastern Pacific, though this may be partly due to the fact that sampling with large nets has been more intensive in the Eastern Pacific. Thus the pelagic species are most sharply separated into different populations in the eastern half of the ocean, where in general the currents are more sluggish. It appears that the slower currents allow more permanent temperature and salinity discontinuities to form and also do not displace populations so far before they are eliminated by adverse environmental factors.

Spatial variations in the concentration of the various species appear to be primarily due to the basic productivity of the local areas that constitute the total distribution. Thus, *Sagitta pseudoserratodentata* (Fig. 12) is most abundant along the edges of its range, where there is a higher standing crop of phytoplankton and zooplankton, than in the interior of the Pacific Central Water, where its concentration appears to be less than one individual in 3000 cubic meters of water. The rapid decrease in abundance of the *S. friderici* population off California, already mentioned, is correlated with a decrease in the standing crop of phyto- and zooplankton. Thus it seems that species abundance is dependent on three major variables—temperature, salinity, and available food as indicated by standing crop.

FUTURE WORK

The present study is based on a very sensitive sampling technique wherein a single specimen may be recovered from 1,000 cubic meters of water, or a sensitivity of about one part in 10^{13} by volume. Yet this sensitivity is not enough. By increasing the net diameter to two meters and by doubling the length of tow it would be possible to increase the sensitivity by almost one order of magnitude. Such a procedure is absolutely essential in the barren Pacific Central Waters if statistically reliable differences are to be demonstrated.

The available plankton samples do not allow a detailed study of time changes in the species limits and concentrations. Where repetitive sampling has been carried out, changes with time have been pointed out.

Subspecific variation has been considered briefly in the discussion of *Sagitta* sp. (*serratodentata* group). Even such well known species as *S. enflata*, *S. hexaptera*, and *S. decipiens* show marked morphologic variations in different parts of their range. The detailed study of these variations should lead to a better understanding of the requirements that the environment imposes on the various species, and should give some clues as to how temperature and salinity are connected to the physiology of the species in limiting its distribution.

The extensive material that has been examined for this work still leaves large gaps in our knowledge of the horizontal, and especially the vertical, distribution of the various species. The water masses are still incompletely defined in many regions, and this may account for some of the discrepancies between the species distributions and the water masses. Most of the expeditions took only oblique net tows so that exact correlation with temperature and salinity is not possible. Despite these great handicaps, with the populations as outlined above as a frame of reference it is now possible to make quantitative vertical sections of the chaetognath fauna and various physical-chemical parameters in local areas and to relate such observations more exactly to the huge moving system, the ocean.

REFERENCES

AGASSIZ, A. 1883. Exploration of the surface fauna of the Gulf-Stream, III, Part I, The *Porpitidae* and *Velellidae*. Mem. Mus. Comp. Zool., Harvard Col., **8** (2): 1–16.

BALDASSERONI, V. 1915. Raccolte planctoniche fatte dalla R. Nave "Liguria" nel viaggio di circonnavigazione del 1903–05. Chaetognati dalle publicazioni R. Instituto di studi superior di Firenze, **2**: 85–118.

BIERI, R. 1956. A method for the microscopic examination and manipulation of plankton on board ship. J. Cons. Int. Explor. Mer, **22**: 37–41.

———. 1957. The chaetognath fauna off Peru in 1941. Pacific Sci., **11**: (3): 255–264.

BIGELOW, H. B., AND M. LESLIE. 1930. Reconnaissance of the waters and plankton of Monterey Bay, July 1928. Bull. Mus. Comp. Zool., **70** (5): 428–581.

BODEN, B. P., M. W. JOHNSON, AND E. BRINTON. 1955. The Euphausiacea (Crustacea) of the Northern Pacific. Bull. Scripps Inst. Oceanogr., **6**: 287–400.

BOGOROV, V. 1946. Zooplankton collected by the "Sedov" Expedition 1937–38. Works of drifting ice expedition in the central Arctic Ocean in ice-breaking steamer "G. Sedov". (in Russian)

BOGOROV, V. G., AND M. E. VINOGRADOV. 1955. Some essential features of zooplankton distribution in the Northwestern Pacific Ocean. Trudy Inst. Okeanologii, Acad. Sci. U.S.S.R., **18**: 113–123. (in Russian)

BOWMAN, T. E. 1955. A new copepod of the genus *Calanus* from the northeastern Pacific with notes on *Calanus tenuicornis* Dana. Pacific Sci., **9**: 413–422.

BRODSKII, K. A. 1952. On the vertical distribution of copepods in the Northwestern Pacific Ocean. Invest. Far East. Seas

(42)

U.S.S.R. III. Deep-water fauna Northwestern Pac. Ocean. Zool. Inst., Acad. Sci. U.S.S.R.: 88–94. (in Russian)

——. 1955. Plankton of the northwestern part of the Kuroshio and the waters of the Pacific Ocean adjacent to the Kurile Islands. Trudy Inst. Okeanologii, Acad. Sci. U.S.S.R., **18**: 124–133. (in Russian)

Dakin, W. J., and A. N. Colefax. 1940 The plankton of the Australian coastal waters off New South Wales. Publ. Univ. Sydney, Dept. Zool. Monogr., **1** (Pt. 1): 63–70.

David, P. M. 1956. *Sagitta planctonis* and related forms. Bull. Brit. Mus. (Nat. Hist.), **4** (8): 437–451.

Ekman, S. 1953. Zoogeography of the sea. Sidgwick and Jackson, London. 417 pp.

Fraser, J. H. 1952. The Chaetognatha and other zooplankton of the Scottish area and their value as biological indicators of hydrographical conditions. Scott. Home Dept. Mar. Res. No. **2**: 1–52.

Furnestin, M. L. 1953. Contribution à l'étude morphologique, biologique et systematic de *Sagitta serrato-dentata* Krohn les eaux atlantiques du Maroc. Inst. Oceanogr., Bul., **50** (1025): 1–39.

——. 1957. Chaetognathes et zooplancton du secteur Atlantique Marocain. Rev. Trav. Inst. Pêches Marit., **21** (1, 2): 1–356.

Graham, H. W., and N. Bronikovsky. 1944 The genus *Ceratium* in the Pacific and North Atlantic Oceans. Sci. Res. Cruise VII of the Carnegie, 1928–29, Biol., **5**: 1–187.

Grey, B. B. 1922. Notes on species of *Sagitta* collected during a voyage from England to Australia. Proc. Roy. Soc. Queensland, **34**: 171–180.

——. 1931. Chaetognatha from the Society Islands. Proc. Roy. Soc. Queensland, **42** (6): 62–67.

Giesbrecht, W. 1892. Systematik und Faunistik der pelagishen Copepoden des Golfes von Neapel und der angrenzenden Meerabschnitte. Fauna u. Flora Golf. Neapel, **19**: 1–831.

Hamon, M. 1956. Chaetognathes recueillis dans la Baie de Nhatrang-Cauda (Viet-Nam). Bull. Mus. Nat. d'hist. Natur., 2^{e}ser., **28** (5): 466–473.

Hida, T. S. 1957. Chaetognaths and pteropods as biological indicators in the North Pacific. U. S. Fish Wildl. Serv., Spec. Sci. Rept. Fisheries, **215**: 1–13.

Hsü, F. 1943. On some species of *Sagitta* of China. Sinensia, **14**: 129–139.

Hubbs, C. L. 1952. Antitropical distribution of fishes and other organisms. Proc. Seventh Pac. Sci. Congr.: 324–329.

Johnson, M. W. 1956. The plankton of the Beaufort and Chukchi Sea areas of the Arctic and its relation to the hydrography. Arctic Inst. N. Amer. Tech. Pap., **1**: 1–32.

King, J. E., and J. Demond. 1953. Zooplankton abundance in the central Pacific. U. S. Fish Wildl. Serv., Fish. Bull., **54** (82): 1–144.

Kusmorskaya, A. P. 1949. On the spring plankton in the northwestern part of the Japanese Sea. Bull. Acad. Sci. Moscow (Biol.), **3**: 375–380. (in Russian)

Lea, H. E. 1955. The chaetognaths of western Canadian coastal waters. J. Fish. Res. Bd. Canada, **12** (4): 593–617.

Maurice, R. 1953. Quelques renseignements sur le plankton des Iles Tuamotu. Bull. Mus. Nation. Hist. Nat., **25** (2): 456–460.

Mawson, P. M. 1944. Some species of the chaetognath genus *Spadella* from New South Wales. Trans. Roy. Soc. Australia, **68** (2): 327–333.

Meek, A. 1928. On *Sagitta elegans* and *Sagitta setosa* from the Northumbrian plankton, with a note on a trematode parasite. Proc. Zool. Soc. London, **1928**: 743–776.

Michael, E. L. 1911. Classification and vertical distribution of the Chaetognatha of the San Diego region. Univ. Calif. Publ. Zool., **8**: 21–186.

——. 1913. *Sagitta californica* n. sp. from the San Diego region including remarks on its variation and distribution. Univ. Calif. Publ. Zool., **2** (5): 89–126.

Pierce, E. L. 1953. The Chaetognatha over the continental shelf of North Carolina with attention to their relation to the hydrography of the area. J. Mar. Res., **12** (1): 75–92.

Ritter-Zahony, R. 1911a. Revision der Chätognathen. Deutschen Sudpolar Exped., **13** (5): 1–71.

——. 1911b. Die Chätognathen der Plankton-Expedition. Ergeb. Plankton-Exped. der Humboldt-Stiftung., **2**: 1–33.

Russell, F. S. 1932. On the biology of *Sagitta*. The breeding and growth of *Sagitta elegans* Verrill in the Plymouth area, 1930–1931. J. Mar. Biol. Ass. U.K., **18**: 131–145.

——. 1934. The zooplankton. III. A comparison of the abundance of zooplankton in the Barrier Reef Lagoon with that of some regions in Northern European waters. Brit. Mus. (Nat. Hist.), Gt. Barrier Reef Exped., Sci. Rpt., **2** (6): 176–185.

——. 1935. On the value of certain plankton animals as indicators of water movements in the English Channel and the North Sea. J. Mar. Biol. Ass. U.K., **20** (2): 309–332.

——. 1937. The seasonal abundance of the pelagic young of teleostean fish in the Plymouth area, Pt. IV. The year 1936 with notes on the conditions as shown by the occurrence of plankton indicators. J. Mar. Biol. Ass. U.K., **21** (2): 679–686.

——. 1939. Hydrographical and biological conditions in the North Sea as indicated by plankton organisms. J. Cons. Int. Explor. Mer, **14** (2): 171–192.

Schilp, H. 1941. IX. The Chaetognatha of the

Snellius Expedition. Biol. Results of the Snellius Exped., **6**: 1–99.

Slabber, M. 1778. Naturkundige Verlustigingen, behelzende microscopise Waarneemingen van in-en Uitlandse Wateren Land-dieren. Te Harrlem, J. Bosch. 1–18.

Sproston, N. G. 1949. A preliminary survey of the plankton of the Chu-San region, with a review of the relevant literature. Sinensia, **20**: 138–141.

Staff, South Pacific Fishery Investigations. 1952. Zooplankton volumes off the Pacific Coast, 1951. U. S. Fish Wildl. Serv., Spec. Sci. Rept., Fisheries, **73**: 1–37.

———. 1953. Ibid, **100**: 1–41.

———. 1954. Ibid, **125**: 1–54.

———. 1955. Ibid, **161**: 1–35.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming. 1942. The Oceans, their physics, chemistry and general biology. Prentice-Hall, New York. 1087 pp.

Tćhindonova, J. G. 1955. (Chaetognatha of the Kurile-Kamchatka Trench.) Trudy Inst. Oceanol., **12**: 298–310. (in Russian)

Thomson, J. M. 1947. The chaetognaths of Southeastern Australia. Com. Sci. Ind. Res. Bull., **222** (Div. Fish. Rept. No. 14): 1–43.

———. 1954. The identity of *Spadella moretonensis* Johnston and Taylor. Proc. Roy. Soc. Queensland, **64**: 44–49.

Tokioka, T. 1939a. Chaetognatha collected chiefly from the Bays of Sagami and Suruga with some notes on the shape and structure of the seminal vesicle. Rec. Oceanogr. Works Japan, **10** (2): 123–150.

———. 1939b. Three new chaetognaths from Japanese waters. Mem. Imp. Observ., Kobe, **7** (1): 129–140.

———. 1940a. The chaetognath fauna of the waters of Western Japan. Rec. Oceanogr. Works Japan, **12**: 1–22.

———. 1940b. A small collection of chaetognaths from the coast of New South Wales. Rec. Australian Mus., **20**: 367–379.

———. 1942. Systematic studies of the plankton organisms occurring in Iwayama Bay, Palao. III. Chaetognaths from the Bay and adjacent waters. Palao Tropical Biol. Sta. Studies, **2**: 527–548.

———. 1951. Pelagic tunicates and chaetognaths collected during the cruises to the New Yamato Bank in the Sea of Japan. Publ. Seto Mar. Biol. Lab., **2**: 1–25.

———. 1954a. XIII. Emergence of a dense patch of chaetognaths near the Laboratory. Publ. Seto Mar. Biol. Lab., **3** (1): 359–360.

———. 1954b. Droplets from the plankton net XVI (printed XIV). On a small collection of chaetognaths from the Central Pacific. Publ. Seto Mar. Biol. Lab., **4** (1): 99–102.

———. 1955a. On some plankton animals collected by the Syunkotu-Maru in May–June 1954. Publ. Seto Mar. Biol. Lab., **4**: 219–225.

———. 1955b. XVII. A small collection of chaetognaths and pelagic tunicates from the north eastern part of the Indian Ocean. Publ. Seto Mar. Biol. Lab., **5** (1): 75–78.

———. 1956. On some chaetognaths and appendicularians collected by Mr. Z. Sagara in the Arafura Sea in May–August 1955. Publ. Seto Mar. Biol. Lab., **5** (2): 203–208.

Uyeno, F. 1952. Reports of plankton 7; (1) Kii Channel regular collection April and July 1951, Kii Channel Oct. 1951, Ise Bay March 1951. Kobe Mar. Obs. (in Japanese).

Wailes, G. H. 1929. The marine zooplankton of British Columbia. Mus. and Art Notes, **4** (4): 159–165.

Wooster, W. S., and F. Jennings. 1955. Exploratory oceanographic observations in the eastern tropical Pacific, January to March, 1953. Calif. Fish and Game, **41** (1): 79–90.

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Venom of the Stonefish Synanceja verrucosa

Abstract. Moderate doses in rabbits produced hypotension, increased respiratory rate, and myocardial injury. Respiratory arrest occurred with fatal doses when the blood pressure had declined to very low values. The active substance (or substances) was nondialyzable, and the potency of the protein-containing lyophilized or glycerol-treated extracts was maintained well on prolonged storage.

Stonefishes of the genus *Synanceja* have caused a number of deaths in human beings through stings by the venomous spines (*1*, *2*). Two large venom sacs are present on each of the 13 dorsal spines, and much smaller ones on two pelvic and on three anal spines (*1*). Wounds have occurred commonly on the hand or foot as a result of punctures by the dorsal spines of the fish, which inhabits shallow water over wide areas of the tropical Indian and Pacific oceans. Extreme pain ensues within a few minutes after the sting and then spreads from the wound over the entire extremity. Ischemia and edema soon appear, and complete recovery from the local effects may be delayed for days or weeks. Systemic effects include weakness, sweating, respiratory distress, and convulsions; death may occur within a few hours (*1–3*). Duhig and Jones (*4*) and Gail and Rageau (*5*) have described the behavior of a few animals injected with stonefish venom; in addition, a hemolytic action has been reported (*6*). However, no data are available on the nature of the systemic effects of the venom or on the properties of the active substance (or substances).

Specimens of *Synanceja verrucosa* Bloch and Schneider were collected at depths of 25 feet or less at Parry Island, Eniwetok Atoll, Marshall Islands, and were maintained alive in the aquarium until used (*7*). The mean weight of the fish was approximately 2 kg; the mean standard length, 30 cm. The 13 dorsal spines were removed, and the thick outer integumentary sheath of each spine was peeled away, revealing two large, attached venom sacs. Extracts were prepared at 3°C, either by slitting open the sacs under 0.9-percent NaCl solution or by aspirating the fluid venom from the sacs and adding it to 0.9-percent saline. The extract was centrifuged at approximately 500 *g* for 5 minutes and the clear, colorless supernatant (*p*H approximately 6.8) was decanted from a small amount of precipitate. Suitable dilutions of the extracts were injected intravenously into tail veins of albino mice (mean weight 25 g). The animals died in about ½ to 30 minutes, depending upon the dose; animals which did not die within ½ hour usually survived indefinitely. Injected venom in amounts fatal within 2 to 5 min produced any or all of the following symptoms initially: ataxia, circling movements, and partial or complete paralysis of the limbs. A period of inactivity usually followed, after which violent rolling or pedaling movements occurred for about 15 seconds prior to respiratory arrest and death.

The undiluted venom aspirated from the sacs (0.03 to 0.07 ml per spine) was a clear, colorless fluid with an average nitrogen content of approximately 2 percent and a protein content (biuret determination) of approximately 13 percent. The total solids amounted to about 14 percent. The mean LD_{50} of freshly prepared extracts in mice was approximately 200 μg of protein per kilogram (range, 148 to 276 μg/kg) or 30 μg of nitrogen per kilogram; 10,000 to 25,000 LD_{50} doses for mice were present in extracts prepared from individual fish. Dialysis of extracts for 24 hours at 2°C in Visking cellulose casing against 0.9-percent NaCl solution indicated that the material lethal to mice was nondialyzable.

Extracts prepared from freshly killed specimens were adjusted to *p*H 7.5 and preserved by lyophilization or by the addition of glycerol to a final concentration of 40 percent. The samples (in sealed glass vials) were maintained for about 1 week in Dry Ice and subsequently were maintained at – 20°C. Bioassays of representative glycerol-treated and lyophilized samples after 1 year of storage have indicated that 50 to 100 percent of the original activity was retained. The symptoms produced in mice with these stored samples appeared identical with those evoked by freshly prepared extracts. Spines were also removed from fish and stored at the afore-mentioned temperatures in sealed polyethylene bags for 10 months; extracts prepared after this period were of comparable potency and produced in mice the same symptoms as did extracts prepared from freshly killed fish.

Experiments were performed to determine the nature of the systemic effects of the venom. Twelve rabbits (average weight about 2 kg) were anesthetized with urethane (1 to 1.5 g/kg) intraperitoneally. Blood pressure was recorded from a carotid artery; the respiration was recorded, and electrocardiographic tracings were obtained simultaneously. Venom extracts were injected into a jugular vein. Lyophilized and glycerol-treated samples produced the same responses. Injection of small doses produced a slight fall in blood pressure

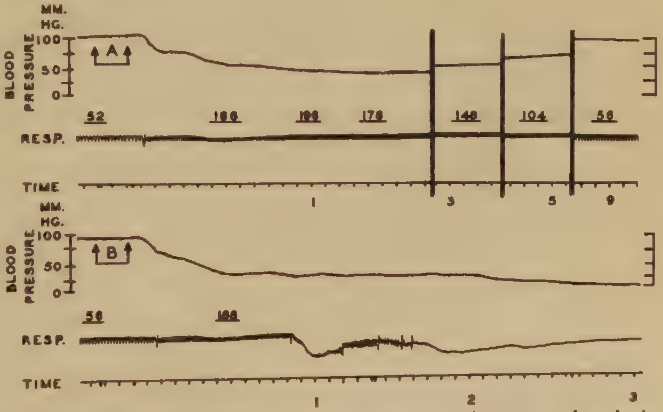

Fig. 1. Effect of venom of *Synanceja verrucosa* upon the blood pressure and respiration of a rabbit. The space between the arrows at *A* (top) indicates the interval during which 7.7 μg of venom protein per kilogram was injected; at *B* (bottom), the interval during which 11 μg/kg was injected 25 min later. The heavy vertical lines in the upper record indicate interruption of the recording. The numbers above the record of respiration indicate the respiratory rate per minute during the time interval denoted by the horizontal lines beneath these numbers. Signal marks at 5-second intervals and the numbers below the signal marks indicate time (minutes) after injection of venom. Inspiration is indicated by the downward stroke on the respiration record.

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accompanied by an increase in respiratory rate, with no electrocardiographic changes; these effects disappeared within about 5 min. Larger doses caused a more marked fall in blood pressure and an increase in respiratory rate which was sometimes accompanied by a period of decreased depth of respiration. There was evidence of myocardial ischemia or injury (inversion of the T wave in some animals, and marked displacement of the S-T segment in all animals), despite the absence of significant changes in the heart rate. All effects had disappeared after about 10 minutes (Fig. 1, *A*).

Injection of fatal doses produced similar effects initially; additional electrocardiographic changes (for example, occasional premature auricular and ventricular impulses, first-degree atrioventricular block, ventricular tachycardia, ventricular fibrillation) occurred as the blood pressure continued to decrease. The respiration then slowed and often became gasping for ½ minute or less and finally ceased in inspiration (in approximately 1.5 minutes in the typical experiment illustrated in Fig. 1, *B*); cardiac standstill followed within a few minutes. The auricles (and sometimes the ventricles) were usually still beating when the chest was opened, approximately 1 minute after respiratory arrest. The mean lethal dose in these experiments was approximately 10 μg of protein per kilogram.

The above results indicate that the primary action of the venom upon the cardiovascular system is the production of a marked hypotension, which is associated in the case of larger doses with injury to the myocardium; whether these cardiac effects are due to a direct action of the venom upon the myocardium or coronary vessels or are secondary to the hypotension remains to be determined (*8*).

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References and Notes

1. B. W. Halstead, M. J. Chitwood, F. R. Modglin, *Trans. Am. Microscop. Soc.* 75, 381 (1956).
2. J. L. B. Smith, *Copeia* 1957, 249 (1957).
3. ———, *ibid.* 1951, 207 (1951).
4. J. V. Duhig and G. Jones, *Mem. Queensland Museum* 9, 136 (1928).
5. R. Gail and J. Rageau, *Bull. soc. pathol. exotique* 49, 846 (1956).
6. J. V. Duhig, *Z. Immunitätsforsch.* 82, 185 (1929); ——— and G. Jones, *Australian J. Exptl. Biol. Med. Sci.* 5, 173 (1928).
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Measurements of the Pacific Equatorial Countercurrent

As part of *Doldrums*, the third of three International Geophysical Year oceanographical expeditions of the Scripps Institution of Oceanography, direct current measurements were made in the centre of the equatorial countercurrent, 7° 52′ N., 107° 30′ W. The techniques were similar to those used three months previously, when measurements were made of the Cromwell current at the equator, 140° W.[1]. In the top 300 m. observations were made by suspending a propeller-type current meter (a modified Roberts

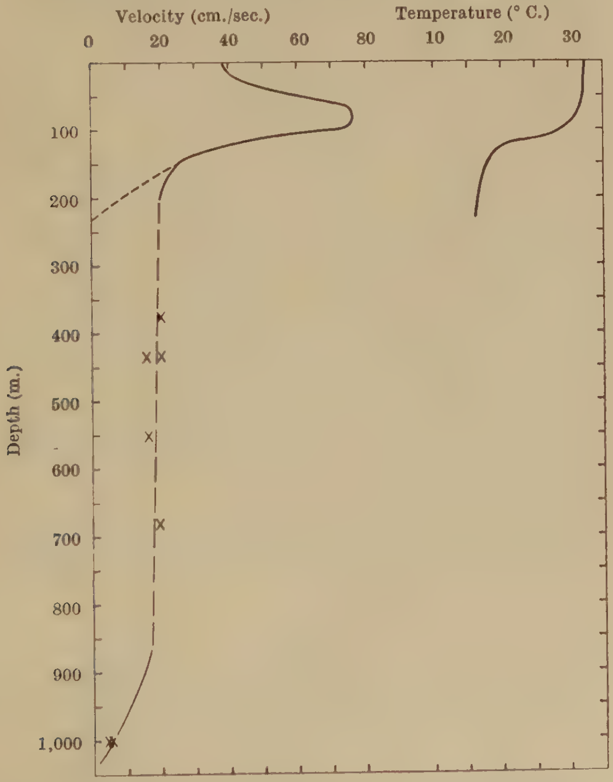

Fig. 1. Current and temperature profile in Pacific equatorial countercurrent, 7° 52′ N., 107° 30′ W. Transport calculation above and below the thermocline were made relative to the dashed line

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meter) from a drifting ship and measuring the apparent velocity at different depths from the flow of water past the meter while at the same time observing by radar the drift of the ship from a fixed reference point—a taut wire buoy anchored in 2,200 fathoms. Below 300 m. measurements were made by following the drift of Swallow current floats[2].

Calculations of the geostrophic current as well as other considerations have led to a picture of the countercurrent as a shallow current the maximum velocity of which is to be found somewhat below the surface, but the flow of which is confined almost entirely to the region in and above the sharp tropical thermocline. Direct current measurements made on *Doldrums* modify this picture. The highest velocities in the countercurrent are found above the thermocline, and the peak velocity is found beneath the surface but in the mixed layer. However, the countercurrent does not vanish beneath the thermocline but continues to flow east at speeds of 15–20 cm./sec. Fig. 1 is a plot of the east–west current component as measured on *Doldrums*. The current profile above 200 m. is a composite of 12 Roberts meter stations taken over a two-week period ; below 200 m. the curve is drawn to the six Swallow current float measurements summarized in Table 1. The depth of the thermocline as measured by the bathythermograph is also shown.

The results summarized in Fig. 1 indicate that the countercurrent transports more water below the thermocline than above it. The width of the countercurrent during this period was 250–300 km. Making some allowance for a decrease in the current near its edges a rough estimate of the transport of the countercurrent based on this one profile is 20×10^6 $m.^3/sec.$ for the region above the thermocline and 30×10^6 $m.^3/sec.$ for that below the thermocline. The estimated transport above the thermocline agrees with that given by Sverdrup[3] for the countercurrent ($20–25 \times 10^6$ $m.^3/sec.$).

The problem of water balance and mass transport in the equatorial Pacific must be re-examined and at least one detailed north–south section of direct

Table 1

Date	Hours tracked	Depth (m.)	Velocity (cm./sec.) — direction (toward)
August 12	7·2	370	20 — 080°
15	12·5	680	20 — 100°
16	16·0	590	16 — 085°
17	14·2	1,000	5 — 085°
18	7·3	1,000	5 — 135°
26	14·9	430	16 — 115°

current measurement stations is required. The measurements of the Cromwell current in May, 1958, showed[1] an eastward transport of 30 × 10^6 m.^{3}/sec. The present observations imply that there is an additional transport of 30 × 10^6 m.^{3}/sec. in the countercurrent below the thermocline. These additions more than triple the total eastward transport in the equatorial Pacific as given by Sverdrup[3].

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Nov. 21.

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[1] Knauss, J. A., and King, J. E., *Nature*, **182**, 601 (1958).

[2] Swallow, J. C., *Deep Sea Res.*, **3** 74 (1955).

[3] Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., "The Oceans" (Prentice-Hall, New York, 1942).

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Natural Water as a Monochromator[1]

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ABSTRACT

Many of the spectral data on the optical constants of natural water are suspect because of errors introduced by light "leakage" outside the stated band of the filter used. The magnitude of this error is computed for a specified water sample under specified natural lighting when measured with a specified detector and filter. The errors are large even for measurements at shallow depths. Methods for avoiding this error are suggested.

For the past twenty years, at least, there has been considerable interest among biologists and oceanographers in measurements of the spectral distribution of natural light in lake or ocean water. It has been common practice in making such measurements to employ glass or gelatine filters over a photo-detector for the purpose of isolating certain spectral regions. More recently interference filters have been substituted to take advantage of the narrower band widths offered by these filters and also to minimize the confusion in assigning a wavelength to the experimental data.

All too few workers have been aware of the pitfalls of this procedure. Some, it is true, realize that their wavelength assignments are not "quite" correct because of "band-width error," as it has been called, but the devastating effect of "band-width error," or "leakage," or "stray light," or whatever one chooses to call it, on deep water data just has not been made obvious.

The purpose of this paper is to demonstrate the magnitude of band-width error on deep water data and to suggest ways of avoiding it.

Two basic thoughts should be evident in what follows:

(1) The experimental values obtained by a photodetector lowered into water will be directly proportional to the summation of the wavelength-by-wavelength product of four wavelength-dependent parameters, *viz*:

(a) the spectral energy distribution of the natural light that gets through the air-water interface (E_λ),

(b) the spectral sensitivity of the photodetector (S_λ),

(c) the spectral transmittance of the filter employed for band-width isolation (T_F), and

(d) the spectral transmittance of the layer of water between the instrument and the surface (T_W).

Thus any experimental value V can be expressed as follows:

$$V = C \sum_{\lambda_1}^{\lambda_2} E_\lambda S_\lambda T_F T_W \, \Delta\lambda \qquad (1)$$

where C is a proportionality constant, and the limits λ_1 and λ_2 are established by one or more of the four parameters.

(2) Deep water is sometimes far better as a monochromatic filter than a glass or gelatin filter, and although the purpose of the filter (T_F) is to control the spectral band width, actual control may in fact be imposed by the water itself.

Let us go back for a moment to the first of these thoughts. It should be obvious that every light measurement (V) will be associated with some spectral distribution. That is to say, as you proceed from one end of the spectrum at some wavelength (λ_1), the value of the product of the four parameters listed above will become a significant part in the measured value V. In the usual case the product will then remain significant throughout some band of wavelengths, but will finally drop until at λ_2 the product has no more significance than it had at λ_1. The measured value V must therefore be associated with the wavelength band

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between λ_1 and λ_2. Also, since the curve of the product vs. wavelength changes with depth, the light measurement will be associated with a different band width at each depth.

If values of the independent parameters are available over a wide spectral range, one can determine the spectral band to be associated with V by computing and plotting this product, $E \cdot S \cdot T_F \cdot T_W$. If this is done at selected depths, the change in the band width and its position in the spectrum can be observed.

The parameters have been defined in such a way that the only one that varies with depth is the transmittance of the water layer between the instrument and the surface (T_W). This transmittance is ordinarily measured with a horizontal cosine collector (flat-plate collector), and the equation used to express the relationship between transmittance and depth is the familiar exponential law

$$T = e^{-kz} \qquad (2)$$

At the present time there is not available a complete table of spectral data for the coefficient k or for the transmittance expressed above. In order to demonstrate the importance of band width error it will be necessary to use some reasonable approximation to such data. Measurements on various bodies of natural water made by this laboratory indicate that at a wavelength of approximately 500 mμ the value of k is about one-half the value of the beam transmission coefficient, α. For the purposes of this calculation the beam transmission values given by Hulburt (1945) have been multiplied by one-half to obtain a table of k values as a function of wavelength. The shortcomings of this approximation will probably be obvious enough. For example, the procedure does not take into account the selective scattering of blue light which would tend to decrease the values of k in the blue region relative to the red region of the spectrum. However, although a factor of 2 in the value of k could alter the present example in detail it will not invalidate the result.

This approximation for spectral values of k has been used together with: (a) spectral data on the energy distribution of natural illumination taken from the *Handbook of Colorimetry* (Hardy 1936); (b) spectral sensitivity data for an RCA 931A multiplier phototube, from the book *Photoelectricity and its Application* (Zworykin and Ramberg 1949); (c) spectral data for a typical "sharp cut-off" red filter (Wratten #29) shown in Figure 1. Using these data the product $E \cdot S \cdot T_F \cdot T_W$ has been computed at 10 mμ intervals. The results of this calculation, after normalization to 100%, are plotted in Figure 2. The effect of the transmittance of three meters of water is almost completely lost compared to the major effects introduced by the multiplier phototube which cuts off the far red end of the spectrum and the Wratten #29 filter which cuts off the blue and green. However, it should not be overlooked that 18% of the signal is coming from wavelengths between 400 and 600 mμ. It should be remembered that the purpose of making these measurements is to determine the transmittance of the water to light

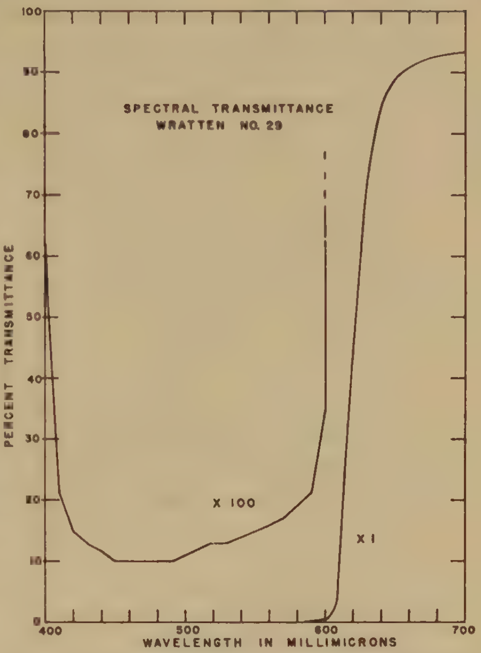

FIG. 1. Spectral transmittance curve for a Wratten #29 filter. The table of published transmittance data for this filter shows no values between 400 and 600 mμ.

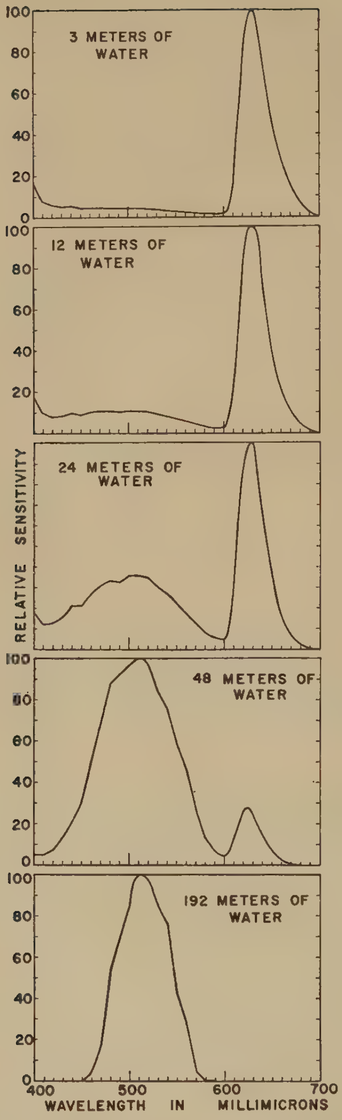

FIG. 2. Relative spectral sensitivity characteristics of a photoelectric detector unit consisting of a multiplier phototube with spectral sensitivity S_{931} equipped with a Wratten No. 29 red filter having transmittance T_{29} when used at five different depths. The spectral distribution of the surface light is defined as E_0 and is fixed. In each case the signal obtained is proportional to the area under the curve and is consequently tagged with the spectral distribution indicated by the limits of the curve.

of a selected band width which has been experimentally specified by the combined spectral characteristics of the filter and the photo detector. If there is a significant relative amount of light leakage outside this selected band an error will be introduced into the reading. In the present example the measurements would normally be assigned a wavelength band between 600 mμ and 700 mμ. Hence the signal coming from wavelengths between 400 mμ and 600 mμ represents an 18% error in the measurements taken with this filter-phototube combination in three meters of ocean water. In twelve meters of water the error has risen to around 32% with the peak wavelength of the major band remaining nearly constant. At a depth of 24 meters the error is around 56% which means that there is more energy being measured outside the red band than is being measured within the band. At 48 meters the measurements have nothing to do with red light at all and at 192 meters we discover that we are measuring monochromatic light of wavelength 510 mμ and half band width of 70 mμ, which is better monochromatic light than was initially provided by the combination of the transmittance properties of the filter and the response properties of the photocell. The interesting result that derives from this example is that no matter what filter or what detector one starts with, if measurements are made deeper and deeper in this water one can look forward to measuring monochromatic light of wavelength 510 mμ at some predictable depth. It follows that for deep-water measurements one must design the optical filter with as much care as was used in designing the mechanical components to withstand the pressure. Otherwise the optical filters will "fail" just as surely as a weak mechanical structure would fail when used at too great a depth.

The effect of this error can be detected in the experimental data of many contributors to the literature on measurement of light in the sea. One example will serve to illustrate. Using the ocean described spectrally above, suppose one measures the upwelling light from the sea and the downwelling light

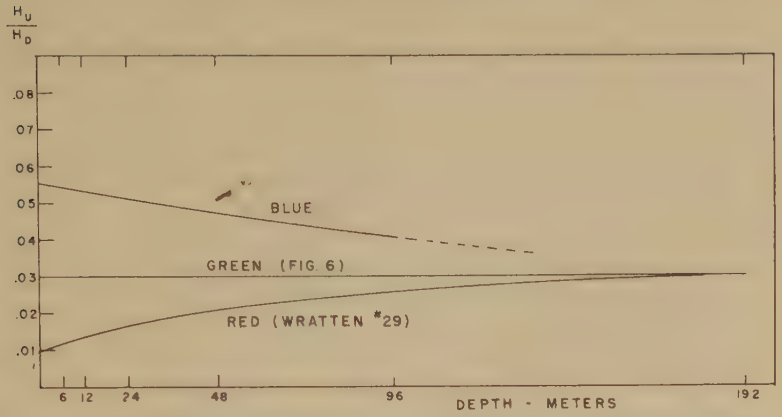

FIG. 3. An example showing the effect of "band-width" error on deep water data. The ratio of upwelling irradiance (H_u) to downwelling irradiance (H_d) is commonly thought of as the reflectance of the water at a horizontal plane beneath the surface. In homogeneous water this reflectance would be expected to remain constant at any one wavelength. In this example as the band width shifts from red to green the ratio H_u/H_d increases accordingly.

from the natural field above in an effort to determine the ratio of these two quantities as a function of depth in homogeneous water. Suppose this work is done using three filters: the Wratten #29 red filter described above, a blue filter having normal leakage characteristics, and a green filter whose transmittance happens to be identical in form with the curve for 192 meters in Figure 2. Near the surface, measurements with these filters will show that the ratio of the upwelling irradiance to the downwelling irradiance (H_uH_d) in the blue region is high (due to the high degree of blue scattering), that the ratio is smaller when the green filter is used, and much smaller with the red filter. Due to band width error, measurements with the red filter at a depth of 192 meters will be tagged with the same spectral band as measurements taken through the green filter, and the two ratios will therefore be the same at 192 meters. Ratios obtained through the blue filter will, for the same reason, exhibit a trend toward the green ratio as depth increases, but may not have reached this ratio at 192 meters, depending on the specific properties of the blue filter. A plot of H_u/H_d vs. depth for the three filters will therefore look like Figure 3.

The design of optical filters for deep water use requires a detailed knowledge of the transmittance properties of the optical components. The transmittance of the filter should be known even though it is only 0.01%. With this information a filter can be designed by combining several separate filters having desirable characteristics. The combination can be made to have minimum transmittance except in the spectral region under study. With such filters one can have confidence in the near-surface values of k (for example). These values can then be used to estimate the band-width error at greater depths, and also the depth beyond which the filter should not be used.

If data within a narrow band are wanted, but the position of the wavelength band is not important, a filter can be used which duplicates the pass band expected for deep water. Such a filter will make the data consistent in band width at all depths.

REFERENCES

HARDY, ARTHUR C. 1936. Handbook of colorimetry. The Technology Press, Mass. Inst. Tech., Cambridge. Table VI, p. 22.

HULBERT, E. O. 1945. Optics of distilled and natural water. J. Opt. Soc. Am., **35:** 698–705.

ZWORYKIN, V. K., AND E. G. RAMBERG. 1949. Photoelectricity and its application. Wiley, New York. 467 pp.

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Measurement of Horizontal Displacement along Faults in the Ocean Floor*

In the eastern Pacific Ocean a right lateral displacement of 84 nautical miles along the Murray Fracture Zone[1] has been suggested by a total magnetic intensity survey[2,3]. The Pioneer Ridge, a newly found east–west fault located between the Mendocino and the Murray Fractures along 38° 30′ north latitude and known to extend between 127° and 136° west longitude, was surveyed by the R.V. *Horizon* of the Scripps Institution of Oceanography of the University of California for the express purpose of measuring the direction and the amount of horizontal slip. A left lateral displacement of 138 nautical miles was found.

The method of measurement depends on the fortunate fact that the magnetic anomaly pattern of the ocean floor revealed by surveys which extend from 32° to 41½° N. lat. and from 125° to 135° W. long., is characterized by north–south trending features with a relief of several milligauss. The two lower curves in Fig. 1 are 15 miles apart and show the north–south alignment of the magnetic pattern. The east–west fractures cut across this pattern so that horizontal slip along a fracture produces a displacement. This is shown in Fig. 1 by a comparison of the uppermost profile taken north of Pioneer Ridge with

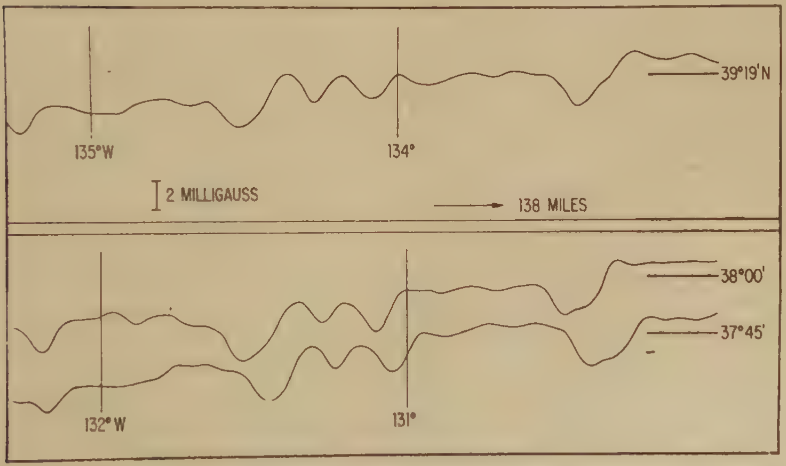

Fig. 1. Profiles of total magnetic intensity on both sides of, and parallel to, the Pioneer Ridge Fault, showing left lateral slip of 138 nautical miles

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the lower pair taken to the south. The uppermost profile is roughly 70 miles north and far to the west. A left lateral fault with a displacement of 138 nautical miles is required to match the pattern. The goodness of fit shows that the amount of distortion accompanying this left lateral slip over a length of 90 miles was less than 10 per cent and implies a remarkable freedom of movement of one crustal block with respect to the other.

The measured displacements along the Murray Fracture Zone and the Pioneer Ridge reveal an unsuspected mobility of small blocks of oceanic crust.

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[1] Menard, H. W., *Geol. Soc. Amer. Bull.*, **66**, 1188 (1955).

[2] Menard, H. W., and Vacquier, V., "Magnetic Survey of Part of the Deep Sea Floor off the Coast of California", Res. Rev. (Office of Naval Research, June 1958).

[3] Mason, R. G., *Geophys. J.* (in the press).

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VOLUME X, PART 2, APRIL, 1959

196. ECOLOGY OF LIVING PLANKTONIC FORAMINIFERA IN THE NORTH AND EQUATORIAL PACIFIC OCEAN[1]

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ABSTRACT

Planktonic Foraminifera were examined from over 700 plankton tows taken at more than 400 stations in the North and equatorial Pacific Ocean. Twenty-seven species were identified and their frequencies determined.

Most specimens occur in the upper 100 m of water. The species appear to be randomly distributed throughout the upper levels with no indication of layering of the abundant species.

The planktonic Foraminifera in the North and equatorial Pacific can be grouped into four faunas: a cold-water fauna, a transition fauna, and two warm-water faunas. The regions they inhabit appear to be differentiated by characteristic temperature and salinity values. The cold-water fauna is limited to the area occupied by the Subarctic Water mass while the warm-water faunas are found throughout the region occupied by the Equatorial and Central water masses.

Highest populations per unit volume of water occur in the Subarctic Water and at limited localities in the equatorial region, lowest concentrations being found in the central oceanic areas. Abundance may be controlled by variations in distribution of inorganic phosphate.

INTRODUCTION

Planktonic Foraminifera are important constituents of the plankton and are major contributors to extensive calcareous deposits covering the ocean floor. They inhabit surface waters of all the oceans from the tropics to the polar seas. It is necessary to understand their ecology to interpret their distributions in modern and ancient sediments and in deep-sea cores. The purposes of the present study are: (1) to determine the species of living planktonic Foraminifera which occur in the North and equatorial Pacific, (2) to describe the distribution and abundance of each species, and (3) to relate the distribution and abundance of the species to known environmental factors.

Most of the laboratory and field work was carried out using ships and facilities of the Scripps Institution of Oceanography. The study was supervised by Fred B Phleger. Frances L. Parker, Jean P. Hosmer, Robert R. Lankford, and Takayasu Uchio of the Marine Foraminifera Laboratory aided in identification of species and with suggestions. Allan H. Bé of the Lamont Geological Observatory sent Atlantic specimens for comparison and made helpful suggestions. Robert H. Bieri aided both in the collection of field data and in discussions regarding the interpretation of the results. James Moriarty drafted many of the illustrations.

PREVIOUS WORK IN THE PACIFIC OCEAN

Work on the ecology of planktonic Foraminifera in the North Pacific has lagged behind that in the Atlantic. Most of the papers include descriptions of bottom specimens dredged near oceanic islands but give little pertinent information about environmental relationships.

The first systematic sampling of living planktonic Foraminifera in the Pacific was carried out by the CHALLENGER in 1874. Forty-five plankton samples, scattered throughout the North and South Pacific, were reported by Brady (1884) and Murray (1895). Agassiz (1902) reported (but did not identify) planktonic Foraminifera from net tows during the voyage of the ALBATROSS (1899-1900) to the tropical Pacific. Three plankton samples from near New Zealand were analyzed for planktonic Foraminifera by Heron-Allen and Earland (1922).

Recently, interest in the ecology of planktonic organisms has led to the systematic collection of thousands of plankton samples by many agencies throughout the world. The Pacific Oceanic Fisheries Investigation (POFI) based at Hawaii has taken many samples in the equatorial Pacific from 1950 to the present. In the early work of this organization various plankton groups (including Foraminifera) were analyzed separately. The reports of King and Hida (1957) furnish extensive information on the variations in abundance of Foraminifera in the equatorial Pacific although no information is given concerning the distribution of species.

METHODS OF STUDY

Field Methods

The Foraminifera studied were from more than 700 plankton samples taken during expeditions of the Scripps Institution of Oceanography, the U. S. Fish and Wildlife Service, the Pacific Oceanic Fisheries Investigation (POFI), and the U. S. Navy Electronics Laboratory (*see* Text fig. 1). Station data including positions, methods of sampling, physical and chemical observations etc., are on file at the Scripps Institution and, in part, at the library of the University of California, Los Angeles. Some of the physical data have been published (Cromwell, 1954; Wooster and Cromwell, 1958). Observations of temperature (Text fig.

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[1] Contribution from the Scripps Institution of Oceanography, New Series Contribution no. 29, Marine Foraminifera Laboratory.

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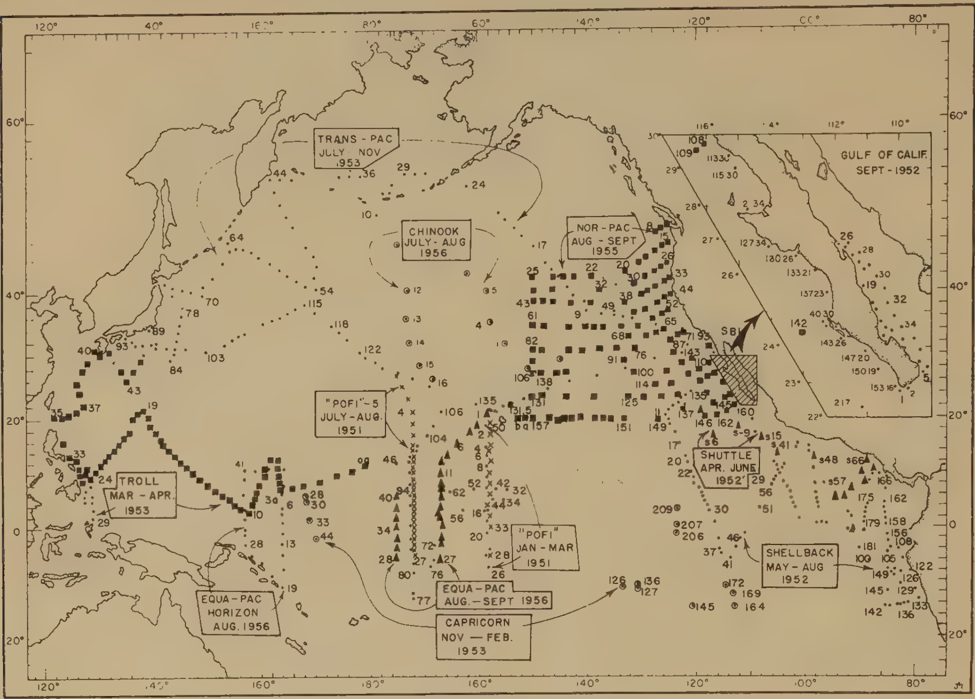
TRANS - PAC
JULY - NOV
1953
CHINOOK
JULY - AUG
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NOR - PAC
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"POFI"-5
JULY - AUG.
1951
TROLL
MAR - APR.
1953
SHUTTLE
APR. JUNE
1952
"POFI"
JAN - MAR
1951
SHELLBACK
MAY - AUG
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EQUA - PAC
AUG.-SEPT 1956
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1953
60°
40°
20°
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20°
120°
140°
160°
180°
160°
140°
120°
100°
80°

TEXT FIGURE 1
Locations of stations.

2), salinity (Text fig. 3) and organic phosphate concentrations (Text fig. 6) are given here.

Three types of plankton nets were used for sampling: the standard one meter net, the 17 cm truncated net, and the Clarke-Bumpus sampler. The meter net has been routinely used by Scripps expeditions and by the POFI program in the Pacific. This net has a mouth diameter of 1 m and a length of approximately 5 m. The front and middle sections are made of no. 30xxx silk grit gauze with apertures of 0.65 mm when new, shrinking to about 0.55 mm after use. The rear section and cod end are of no. 56xxx silk grit gauze with effective apertures of 0.31 mm. A current meter is fitted in the net mouth to record the approximate amount of water filtered. A detailed description of this net has been given by King and Demond (1953). By adding a non-filtering canvas section for a puckering line this same net was used as a closing net to obtain uncontaminated deep samples during the Norpac Expedition.

The 17 cm net consists of two sections, a non-filtering, truncated front portion and a filtering cone-shaped rear section. The non-filtering section has a mouth diameter of 17 cm and a length of 15 cm. The filtering portion, which is 46 cm long, has a diameter at the forward end of 24 cm, becoming narrower toward the cod end. The cod end is an 8 oz. glass jar with a diameter of 5 cm. The truncated front section is of muslin, the rear section of no. 20 bolting silk (average opening 0.07 mm).

The Clarke-Bumpus sampler (Clarke and Bumpus, 1940) will record the approximate quantity of water filtered and can be made to open and close at any desired depth. In the present work it was fitted with nets of either no. 8 or no. 20 bolting silk with apertures of 0.14 mm and 0.07 mm respectively.

The oblique tows were made by lowering the net slowly at uniform speed and, when the required depth was reached, raising it at a uniform rate of approximately 5 m per minute. Throughout the period of the haul the time and wire angle were noted. Depth and duration of tow at each depth were calculated by assuming that the towing wire describes a straight line. Approximately equal amounts of time were spent at all depths from the surface to the greatest depth sampled. Horizontal tows for study of vertical distribution were made with the same equipment but the net was opened by messenger at predetermined depths. Vertical hauls with the 17 cm net were made while the boat was stopped. The net, with a weighted cod end, was attached to a light line and lowered slowly by hand to the maximum depth and then retrieved at a rate of approximately one-half meter per second. Plankton clinging to the upper part of the net was washed into the cod end and transferred to a sample jar. Neutralized formalin was added to make a 5 to 10 per cent solution.

Laboratory Methods

The rose Bengal staining technique described by Walton (1952) was used in the early stages of the work to distinguish living from dead specimens. Staining procedures were used in the analysis of samples for vertical distribution studies but the routine staining of samples from the upper water layers was discontinued when it was observed that most of the Foraminifera contained protoplasm. The use of stains in analyzing plankton samples is time-consuming, makes identification more difficult, and often decreases the usefulness of the sample for other purposes. Furthermore, the living specimens can usually be distinguished from the empty tests by the color of their unstained protoplasm. It is possible that some empty tests have been included in the counts of each species. The error caused by these few extra tests in samples from the upper layers is believed to be insignificant, particularly in view of the much larger errors involved in other phases of plankton sampling.

The entire sample was poured into a gridded, plastic counting tray. It was found that frequently the lighter elements of the plankton could be decanted from the tray leaving the Foraminifera and pteropods behind. An efficient separation could be made in tropical samples where the foraminiferal tests were large and heavy but when smaller specimens (usually spinose) occurred this was not true. The plankton was distributed evenly in the tray and all specimens of Foraminifera were examined. Those smaller than 140 μ, with the exception of *Globigerinoides* cf. *G. minuta,* were excluded from the counts since identification of these small forms is subject to error. All the specimens from samples containing fewer than 200-300 specimens were counted. In many larger samples, the more abundant forms in a known fraction were counted, although the entire sample was used for counting the rarer ones. Several specimens of each species were picked by pipette from each sample for reference. Distributions of each species are shown in Text figures 7-33. More detailed information on occurrences of species and the population per 1000 m^3 is on file, as previously mentioned.

Effect of Different Sampling Methods

Ideally, to sample the entire foraminiferal population of an area, *all* the specimens in a water sample of known volume should be counted. This was done by Hentschel (1934) for *Globigerina.* In one-liter samples of the surface water from many localities in the Atlantic he found the number to vary from 0 to 50 specimens of all size groups. The individuals from such small samples, however, were mostly small forms which were difficult to identify. To obtain a sample containing sufficient specimens for accurate species identification much larger quantities of water must be collected. The difficulties involved in handling and analyzing such large volumes of water are so great that fine-mesh nets have almost always been used for routine sampling. Presumably some of the very smallest individuals are still lost but since identification of these is almost impossible at present this loss does not alter the data on species distributions obtained.

It is believed that the 17 cm net and the Clarke-Bumpus samplers with fine-mesh nets sample the smaller specimens adequately, since the aperture of the netting used is fine enough to prevent all but the smallest stages from passing through. However, the smaller volume of water filtered (1-4 m^3), as compared with approximately 1,000 m^3 for the meter net, results in the inadequate sampling of rare species and larger forms. A further disadvantage of fine-mesh nets is that they retain large quantities of phytoplankton which makes foraminiferal analysis difficult.

The meter net filters large quantities of water (approximately 1,000 m^3 for a 30-minute tow) and obtains large numbers of easily identifiable specimens with very few phytoplankton. Since the effective aperture of the front section of the net is relatively large (0.55 mm), many smaller individuals may pass through and not be represented proportionately in the sample. Some specimens of smaller size, nevertheless, are still found in the sample, probably because they are retained by the finer section of the net. This may be due also to the spinose nature of the specimens and some decrease of mesh size by clogging.

The use of samples obtained with three different nets and three different mesh sizes introduces problems in interpretation of results. Comparisons between the total number of specimens of Foraminifera retained by nets of the different mesh sizes (0.55 mm and 0.14 mm) taken during the Transpac Expedition show that for the same depths and volume of water filtered the tow using the finer mesh caught from 9 to 370 times as many specimens as that using the coarser net. Similar results are indicated by data presented by King and Hida (1957). In their work a comparison was made of the effect of two different mesh sizes on the plankton volume, the number of zooplankters per unit of water strained, and the percentage composition of the catch. Pairs of consecutive hauls, the first with a net of 0.31 mm apertures and the second with a net having apertures of 0.55 mm, were made at three stations in the equatorial region. King and Hida found that the average plankton volume obtained by the finer mesh nets for the same volume of water filtered was from 1¼ to 1¾ times that of the coarser mesh nets. The fine-mesh nets retained three to five times as many organisms as the coarse-mesh nets, the greatest difference being in the larger numbers of Foraminifera and copepods retained in the fine-mesh nets.

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Variations Due to Patchiness

In some areas the drawing of closely spaced isopleths showing Foraminifera concentrations has not been possible because of extreme fluctuations in numbers from adjoining stations. Certain other regions, however, show generally consistent values over wide areas. The patchiness of plankton has been noted by many workers and contributes an unknown source of error in quantitative sampling. The filtering of a large volume of water over long horizontal distances may minimize variations due to uneven distributions.

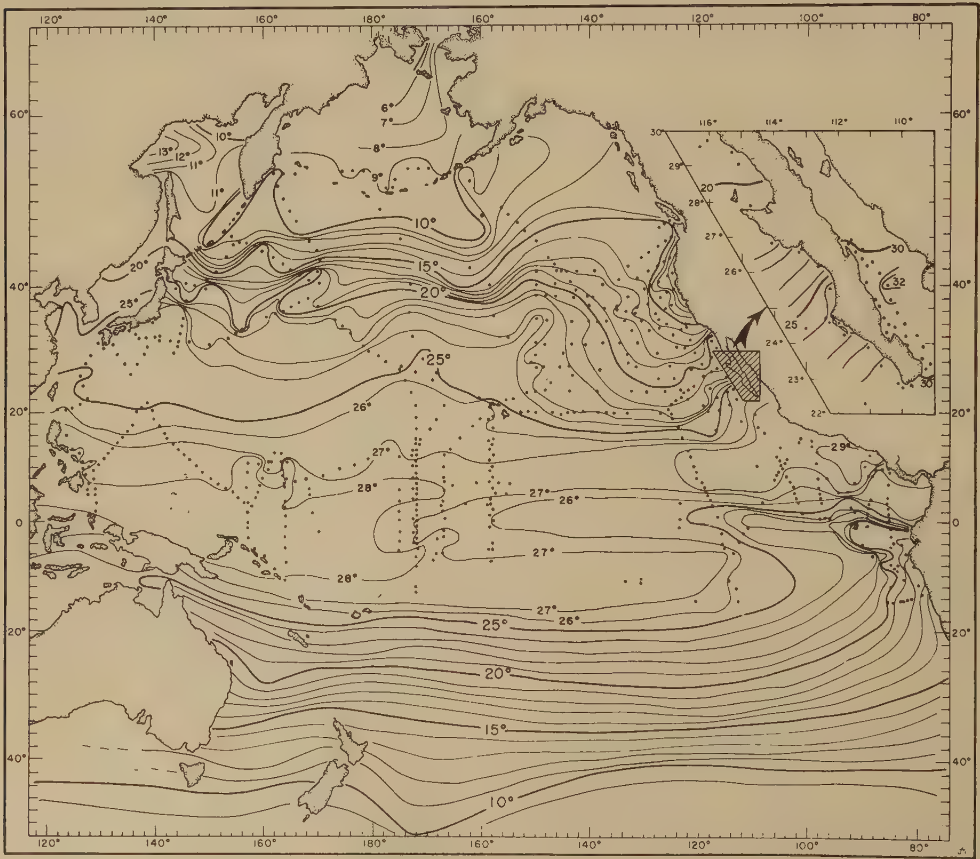
Not so well-known are the facts that the vertical distribution of Foraminifera and the depth of the water filtered by the net also will influence the quantitative results. For example, an oblique tow to 200 m samples the upper 50 m only 25 percent of the time. If the bulk of the population is in the surface layers of 0 to 50 m depth, such a tow will indicate a smaller number of specimens per unit volume than actually occurs at the level of maximum concentration.

Certain irregularities have been introduced in this study by considering all stations equally, regardless of season or time of day. More detailed studies of seasonal and diurnal variations will be necessary to understand fully the variations caused by these factors.

DESCRIPTION OF THE ENVIRONMENT

General Features

The area of investigation includes the North Pacific and a part of the South Pacific extending to approximately 16° S Lat. The physical oceanography of this large area is complex. Distributions of sea-surface temperature (Text fig. 2) are primarily related to the greater heating of the water in the tropics than in higher latitudes. The salinity values (Text fig. 3) are dependent upon the relation between the processes of evaporation and precipitation with the result that the maximum salinities are found not in the equatorial regions but in the sub-tropical belt. Nevertheless, there is a general correlation between surface temper-



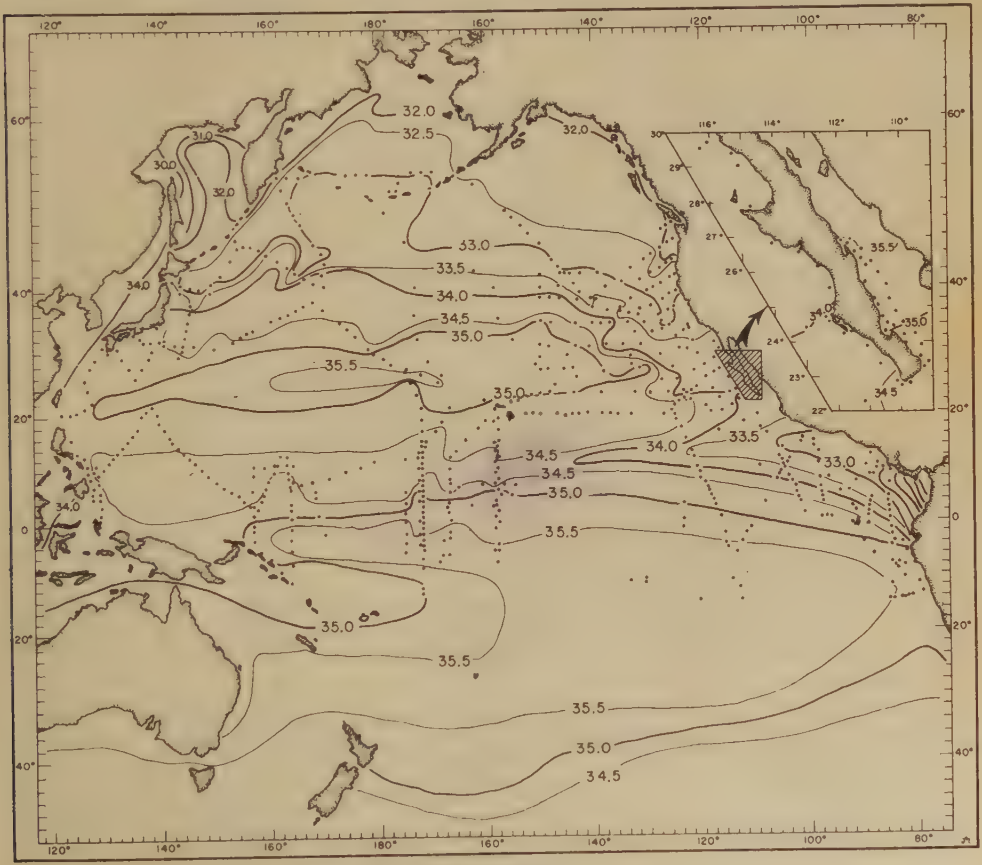
TEXT FIGURE 2

Distribution of sea surface temperatures (°C). N. Pacific values at time of collection; S. Pacific values for August (after Sverdrup *et al.*, 1942) atures and salinities so that high temperatures usually are associated with high salinities and low temperatures with low salinities. The greatest horizontal change in these variables occurs in the North Pacific at the Arctic Convergence (or Polar Front) near 40° N Lat. The steepest gradients are found in the western North Pacific off Japan, whereas the eastern North Pacific is characterized by less abrupt changes.

Prevailing winds and the density structures of the various water masses have resulted in a series of clockwise circulations for the North Pacific (*see* Text fig. 4). The North and South Equatorial currents flow westward between the equator and Lats. 20° to 25° N and sandwiched between (in Lats. 5° to 10° N) is the Equatorial Countercurrent flowing to the east. Near the Philippine Islands the North Equatorial Current divides, part turning north to become the warm Kuroshio. Along the Japanese coast at about 35° N Lat. the Kuroshio turns seaward and divides into two branches. The smaller northern branch continues to the northeast where it mixes with the cold, low salinity Oyashio flowing down from the north. The main stream continues to the east as the warmer North Pacific Current and sends off numerous eddies to the south as it goes.

Along the boundary of the Kuroshio and Oyashio, mixing of the surface waters results in the formation of the cold Subarctic Current which flows eastward between the Aleutian Islands and Lat. 42° N. Upon reaching the American west coast most of the water turns southward as the broad, cool, low salinity California Current, which can be traced to about Lat. 25° N where it merges with the North Equatorial Current to complete the major current gyre in the North Pacific.

The combination of density differences, due to unequal heating and evaporation at the surface, and the action of surface currents have resulted in the formation of large semi-permanent masses of water having certain characteristic properties. These large bodies of



TEXT FIGURE 3
Distribution of sea surface salinities (o/oo)

water are called *water masses* and are defined oceanographically on the basis of their temperature and salinity distributions. The characteristic temperature and salinity values reflect to some extent the climate of the source region. As currents move this water from its place of origin, mixing occurs with other waters, but the various sources can still be recognized. Water masses undoubtedly have other physical and chemical characeristics that are as yet too subtle for analysis but which may be important for various constituents of the plankton. Text figure 4 shows the geographic extent of the upper water masses of this region.

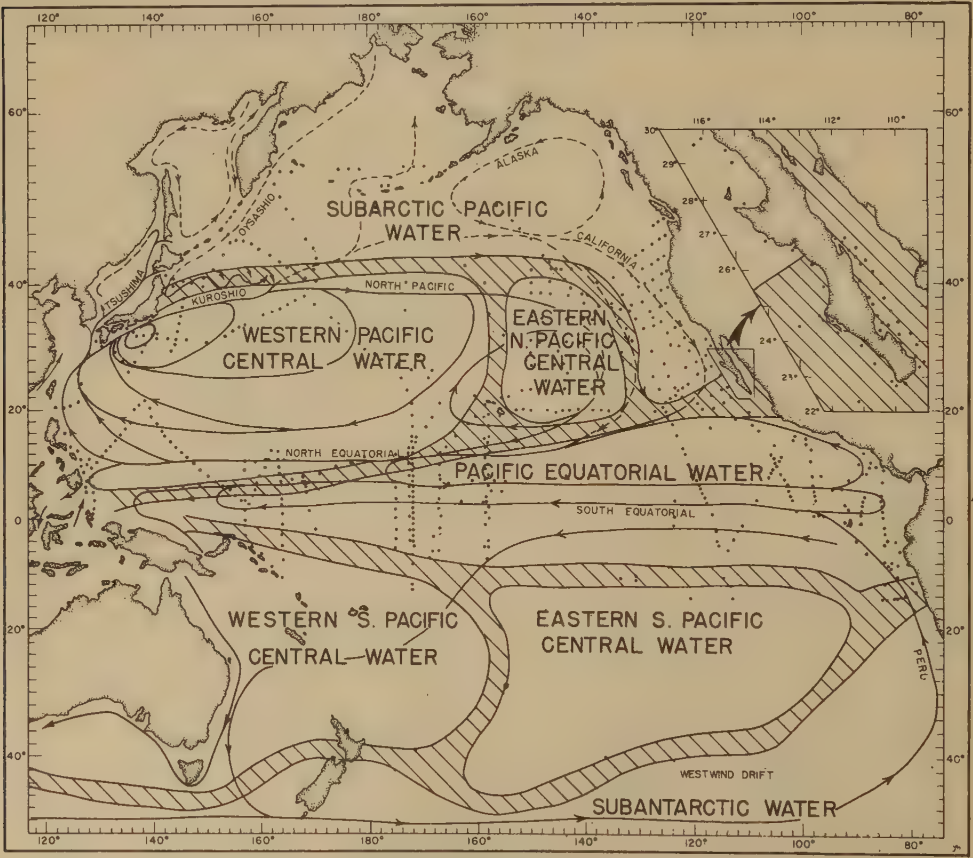
Subarctic North Pacific Region

Subarctic Water is found north of Lat. 45° N where it is characterized at the surface by low temperatures and salinities (*see* Text fig. 5). North of the Aleutian Islands, the surface temperature varies from near 0° C in the coldest month (February) to about 8° C in the warmest (August). Surface currents transport large amounts of this water toward the east and south along the west coast of North America. As it travels from the source region the temperature and salinity increase so that the water gradually loses its subarctic character. The greatest annual temperature range (21° C) occurs at approximately 40° N Lat. near Japan. From this maximum value the temperature range decreases toward the northeast and east to approximately 5° C off the coast of North America (Lat. 40° N).

The surface phosphate concentration is generally high throughout this region (*see* Text fig. 6). Wooster (1953, p. 50) reports a sharp increase just south of the boundary between the Aleutian and North Pacific currents, and high values throughout the area to the north.

Transition Region (California Current)

Sverdrup *et al.* (1942) limit this region to the area between Lats. 48° and 23° N where the southward-flowing Subarctic Water converges with the Equatorial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SUBARCTIC PACIFIC WATER
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OYASHIO
CALIFORNIA
TSUSHIMA
KUROSHIO
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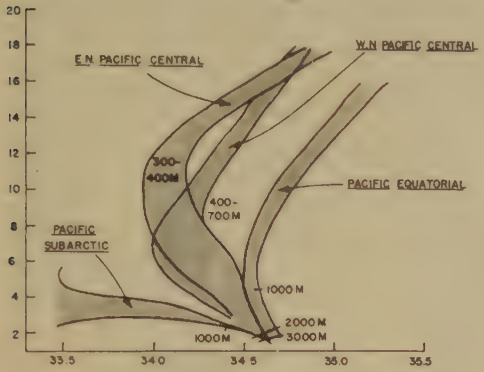
TEXT FIGURE 4

Approximate boundaries of the upper water masses of the Pacific Ocean together with course of the major ocean currents.

Water. The western extent is represented by the boundary of the Subarctic and the North Pacific Central waters. The annual surface temperature range is not extreme, varying from approximately 7° C in the northwest to 3° C in the southwest. Near the coast the seasonal range varies from 3° C along the coast of Washington to 6° C at various localities along southern California and Baja California. This region is dominated by the southward, slow-moving California Current, but seasonal changes in the upper layers cause more complex conditions in certain localities.



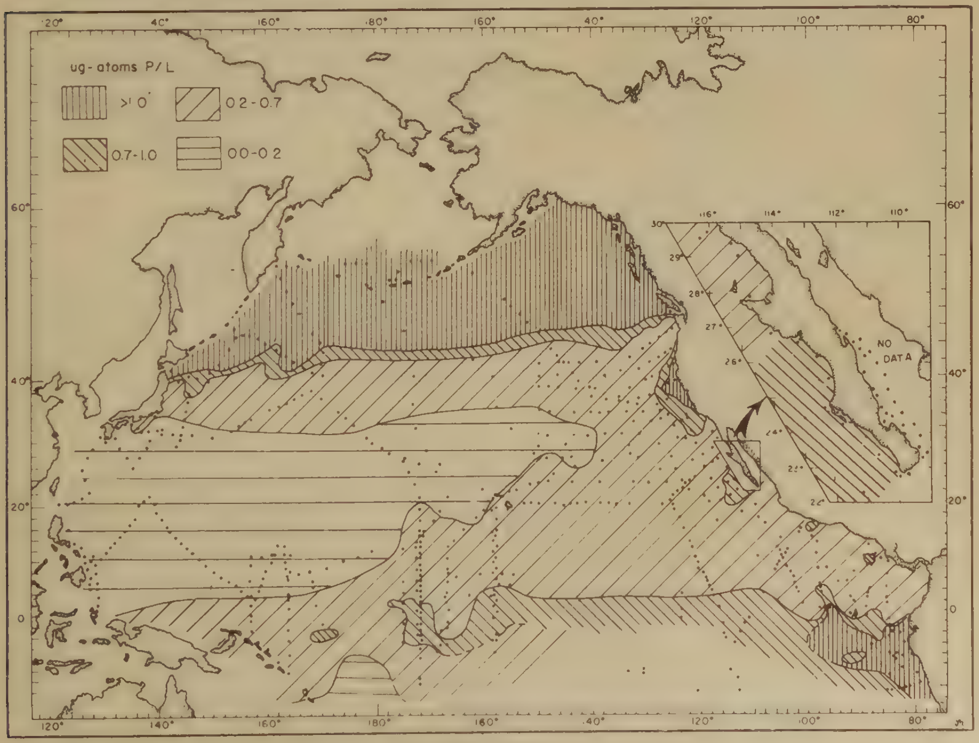
TEXT FIGURE 5

Temperature-salinity relations of the surface water masses of the North Pacific Ocean.

Sverdrup and Fleming (1941) report a subsurface counter current (below 200 m) close to the coast carrying large quantities of Equatorial Water northward. In the fall and winter this water is present at the surface as the Davidson Current, which flows north on the coastal side of the California Current at least as far as Lat. 48° N. The predominance of northwesterly winds, together with sharp breaks in the coastline, result in the offshore transport of surface water causing upwelling of cold subsurface water at various points along the coast. There is some upwelling throughout the year but the strongest occurs during spring and early summer. In this region upwelling returns nutrients, including relatively high concentrations of phosphate, into the euphotic zone so that usually there is an increase in phyto- and zooplankton production.

North Pacific Central Region

In general, the water masses characteristic of this region have properties intermediate between the Subarctic Water and the Equatorial Water. The eastern



TEXT FIGURE 6

Distribution of inorganic phosphate in the surface layers (information taken from various sources).

portion, extending from the longitude of Hawaii to the transitional water of the California Current, differs slightly in its temperature-salinity character from the larger western expanse and has been designated as a separate water mass. This Eastern North Pacific Central Water is distinguished from the Western North Pacific Central Water by lower salinity values at depths of 300-400 m. In the center of the western North Pacific gyral the yearly temperatures vary from a minimum of 23° C to a maximum of 27.5° C. The annual range decreases towards the south and east from a maximum of 12° C off Japan to less than 2° C at the northern boundary of the California Current.

Graham and Moberg (1944) report that the surface phosphate values throughout this region are extremely low, with the low concentrations extending to considerable depths. They associated the low values with the steep density gradients and the poorly-developed current systems, both of which prevent upwelling of phosphate-rich water.

Equatorial Pacific Region

This region includes part of the equatorial warm-water belt which in the eastern Pacific lies between Lats. 18° S and 20° N. Towards the west it becomes narrower and finally disappears at the equator north of New Guinea.

In this area a mixed layer extends from the surface downwards to a narrow transition zone, below which lies the true Equatorial Water mass of very uniform character (*see* Text fig. 5). The base of the mixed layer varies from a depth of 50 m in the east to deeper than 150 m in the western Pacific. In the region of the equator, upwelling caused by the divergence of the surface water brings this base nearer the surface. The annual range of temperature is small over most of this region, the greatest changes occurring south of the Galapagos Islands (5° C annual range) and at the zones of upwelling along the equator. Throughout most of the region the seasonal range of temperature varies only 1-2° C.

THE SPECIES OF PLANKTONIC FORAMINIFERA

General Statement

Planktonic Foraminifera immersed in sea water are different in appearance from dried specimens. This fact, together with the presence of long, thin spines in many species and the presence of protoplasm and organic detritus, increases the difficulty of identification. This is particularly true of small specimens and, therefore, the identification of specimens with a diameter smaller than 140 μ was not attempted, except for the extremely small species *Globigerinoides* cf. *G. minuta*.

Since this was not primarily a taxonomic study, the nomenclature used by Phleger, Parker and Peirson (1953) in their study of North Atlantic Foraminifera has been used for simplicity. Since the completion of this work some of the generic designations have been questioned by various authors (*see* Bolli, Loeblich and Tappan, 1957, Hofker 1959, etc.) Admittedly the taxonomy needs revision but the author feels that our lack of knowledge of internal structure and the biological relationships of the planktonic species does not permit us to clarify the status of these forms at the present time.

A detailed synonymy and taxonomic discussion of each species is not given. The synonymies include the original reference and others of special interest. Species not listed by Phleger *et al.* (1953) are briefly described and a short summary of the information gained through this study is included. The species are listed in alphabetical order. Figured hypotypes have been deposited at the U. S. National Museum, Washington, D. C.

SYSTEMATIC DISCUSSION

Candeina nitida d'Orbigny

Plate 7, figure 19

Candeina nitida D'ORBIGNY, 1839, *in* DE LA SAGRA, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 108, pl. 2, figs. 27, 28.

This species (Text fig. 7) is found in the tropical and warm-temperate regions of the Pacific with its

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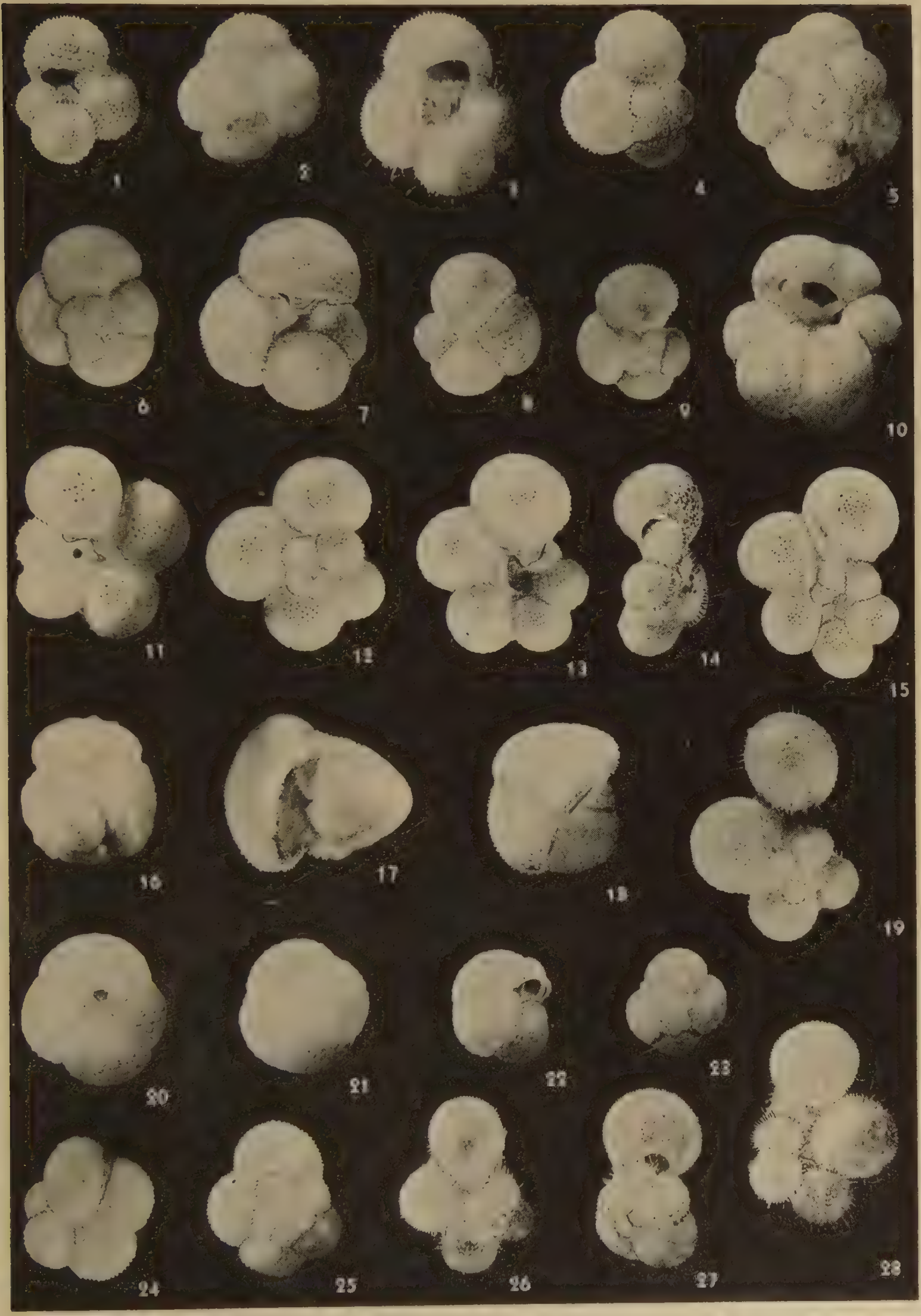
EXPLANATION OF PLATE 6

FIGS.		PAGE
1-4.	*Globigerina bulloides* d'Orbigny. × 67. 1, 4, Shellback sta. 136; 2, 3, Transpac sta. 32	33
5, 8-10.	*Globigerina eggeri* Rhumbler. × 65. 5, 10, adult specimens; 8, 9, juvenile specimens. Transpac. sta. 13	35
6, 7.	*Globigerina conglomerata* Schwager. 6, × 47; 7, × 31. Equapac-s sta. 21	33
11-15.	*Globigerina hexagona* Natland. × 65. 11, 12, Shellback sta. 76; 13-15, variant form, Shellback sta. 61	36
16-18.	*Globigerina inflata* d'Orbigny. × 65. Transpac sta. 108	36
19, 26-28.	*Globigerina* sp. × 47. Equapac-s sta. 21	38
20-23.	*Globigerina pachyderma* (Ehrenberg). 20, 21, × 102, Transpac sta. 32; 22, 23, variant forms, × 65, Transpac sta. 22	36
24, 25.	*Globigerina quinqueloba* Natland. × 102. Transpac sta. 15	38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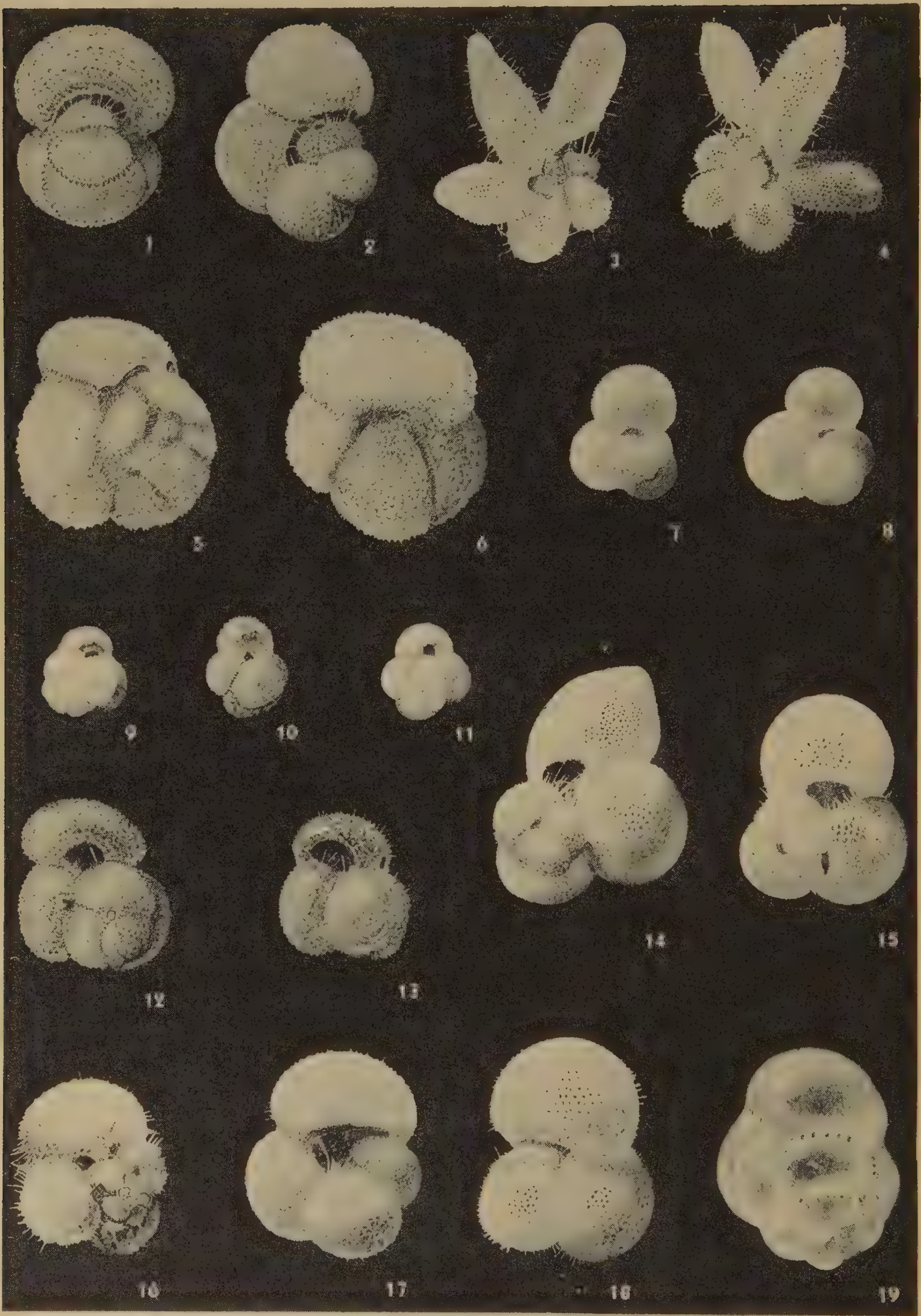
Bradshaw: Living Planktonic Foraminifera, Pacific Ocean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Bradshaw: Living Planktonic Foraminifera, Pacific Ocean

maximum concentration near the Hawaiian Islands. Patches with lower concentrations occur within the Equatorial Water from Panama to the Philippines.

Globigerina bulloides d'Orbigny
Plate 6, figures 1-4

Globigerina bulloides D'ORBIGNY, 1826, Ann. Sci. Nat., vol. 7, p. 277, no. 1; Modèles no. 76; and young, no. 17.

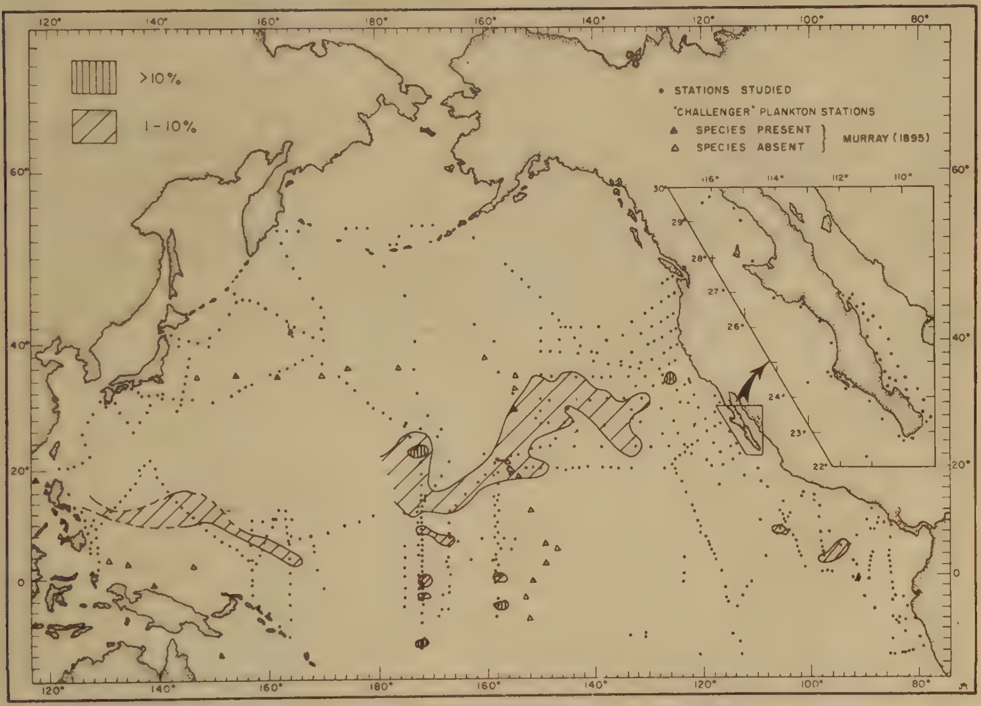
The Pacific specimens are slightly more compact than those reported by Phleger *et al.* (1953) from the Atlantic but it is doubtful that this constitutes a specific difference.

There has been some confusion in the literature regarding this species. Some authors (for example, Cushman, 1914, 1927) have included in their "*G. bulloides*" forms which are now included in *Globigerinoides sacculifera*.

Highest frequencies (Text fig. 8) occur in northern latitudes and occasionally low frequencies were noted in equatorial waters. *Globigerina bulloides* shows the closest affinity to the "cold-water fauna." In temperate latitudes it occurs throughout the water column sampled. Rare occurrences in deep oblique hauls in the equatorial Pacific suggest that it may live at greater depths in this region.

Globigerina conglomerata Schwager
Plate 6, figures 6, 7

Globigerina conglomerata SCHWAGER, 1866, Novara-Exped., Geol. Theil, vol. 2, p. 255, pl. 7, fig. 113.

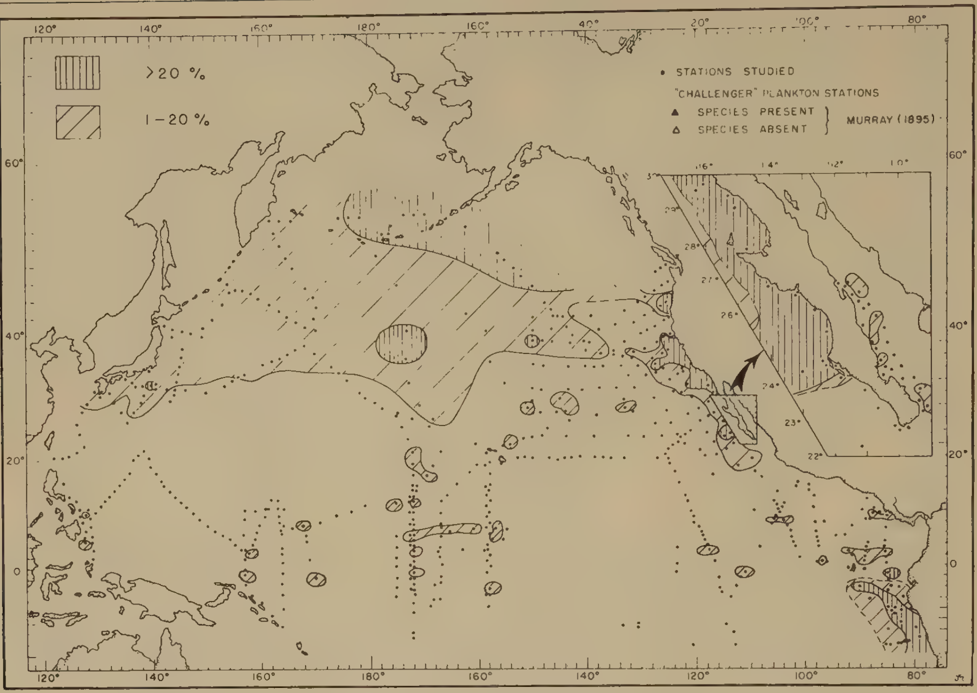


TEXT FIGURE 7

Distribution of *Candeina nitida* d'Orbigny

EXPLANATION OF PLATE 7

FIGS.		PAGE
1, 2.	*Globigerinella aequilateralis* (Brady). × 47. Equapac-s sta. 21	38
3, 4.	*Globigerinella* sp. × 31. Troll sta. 14	38
5, 6.	*Globigerinoides conglobata* (Brady). × 47. Troll sta. 17A	40
7, 8.	*Globigerinita glutinata* (Egger). × 65. POFI-5 sta. 20	40
9-11.	*Globigerinoides* cf. *G. minuta* Natland. × 102. Transpac sta. 51	40
12, 13.	*Globigerinoides rubra* (d'Orbigny). × 65. Equapac-s sta. 21	42
14, 15, 18.	*Globigerinoides sacculifera* (Brady). × 47. Shellback sta. 80	42
16, 17.	*Globigerinoides* sp. × 47. Shellback sta. 30	42
19.	*Candeina nitida* d'Orbigny. × 47. Troll sta. 16A	32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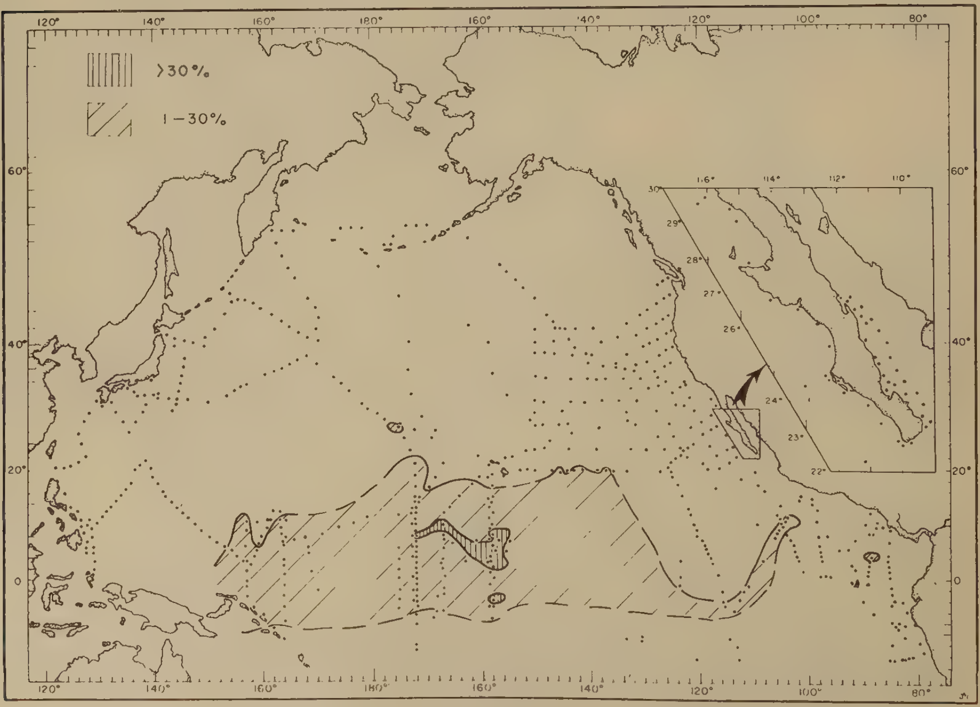
TEXT FIGURE 8
Distribution of *Globigerina bulloides* d'Orbigny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TEXT FIGURE 9
Distribution of *Globigerina conglomerata* Schwager

This species superficially resembles *G. bulloides* in having four chambers in the last-formed whorl but differs from it in having a slightly less lobate and more massive structure and an aperture which is smaller and not so smoothly rounded. The last chamber has a characteristic triangular shape, often with a lip extending partially into the aperture.

This form has been confused by some authors with *G. eggeri* Rhumbler. Brady (1884, p. 596), for example, after examining specimens of *G. conglomerata* from Kar Nicobar considers them to be almost identical with his "*G. dubia*" Egger" (= *G. eggeri*). Cushman's (1921, 1927) records of "*G. conglomerata*" from the west coast of North America and the Philippines are doubtful in view of his confusion of this species with *G. eggeri*.

This is the first recorded occurrence of this species from plankton tows. It is confined to the equatorial Pacific (Text fig. 9).

Globigerina digitata Brady

Globigerina digitata Brady, 1879 (part), Quart. Jour. Micr. Sci., vol. 19, p. 72; 1884 (part), Rept. Voy. CHALLENGER, Zool., vol. 9, p. 559, pl. 80, figs. 6-10 (*not* pl. 82, figs. 6, 7).

Brady appears to have included two distinct species in his *G. digitata*. Parker (1958) has designated the trochoid form as *G. digitata* and has referred the planispiral form to the genus *Globigerinella*. *Globigerina digitata* occurs rarely in the region studied.

Globigerina eggeri Rhumbler

Plate 6, figures 5, 8-10

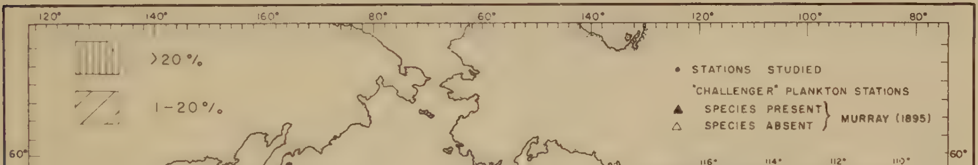
Globigerina bulloides form no. 3, Owen (not d'Orbigny, 1826), 1868, Jour. Linn. Soc., vol. 9, p. 157, pl. 5, fig. 9.

Globigerina dubia Brady (not Egger, 1857), 1879, Quart. Jour. Micr. Sci., vol. 19, n. ser., p. 71; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 595, pl. 79, fig. 17.

Globigerina cretacea Brady (not d'Orbigny) (= *G. subcretacea* Lomnicki), 1884 (part), Rept. Voy. CHALLENGER, Zool., vol. 9, p. 596, pl. 82, fig. 10 (not fig. 11).

Globigerina eggeri Rhumbler, 1900, Nordische Plankton, pt. 14, Foraminiferen, p. 19, text fig. 20.

There appears to be a gradational series between typical large, highspired *G. eggeri* and other forms such as *G. subcretacea*. Juvenile specimens are occasionally difficult to distinguish from forms similar to "*G. dutertrei*" (*see* Ovey *in* Wiseman and Ovey, 1950) and *G. pachyderma*. In this study *G. eggeri*, "*G. subcretacea*" and young specimens of *G. eggeri* and/or *G.*



TEXT FIGURE 10
Distribution of *Globigerina eggeri* Rhumbler

pachyderma-"*dutertrei*" are grouped together because of the difficulty of positive identification, particularly of their young stages.

Specimens of the *G. eggeri* group as defined above are found throughout the warm-water, transitional and subarctic regions of the Pacific. The frequency of occurrence varies, reaching a maximum in the transition areas of the California Current, Peru Current and areas of mixing between cold and warm water such as the junction of the Kuroshio and Oyashio currents northeast of Japan.

Typical adult *G. eggeri* (Pl. 6, figs. 5, 10; Text fig. 10) is not found throughout the above range but is limited to the warm and transitional regions.

Globigerina hexagona Natland

Plate 6, figures 11-15

Globigerina hexagona NATLAND, 1938, Bull. Scripps Inst. Oceanography, Tech. Ser., vol. 4, no. 5, p. 149, pl. 7, fig. 1.

It is possible that several distinct forms have been included with this species. Figures 11 and 12 illustrate the form closest to Natland's. Figures 13-15 show a more compressed form that occurs within the same geographic range. The highest frequency (Text fig. 11) is in the equatorial west-central region with scattered occurrences in the transitional waters of the Peru and California currents.

Globigerina inflata d'Orbigny

Plate 6, figures 16-18

Globigerina inflata D'ORBIGNY, 1839, *in* BARKER-WEBB and BERTHELOT, Hist. Nat. Îles Canaries, vol. 2, Foraminifères, p. 134, pl. 2, figs. 7-9.

Like *Globorotalia truncatulinoides*, this species (Text fig. 12) is most common in the central-water fauna extending from California almost to Japan and from Lats. 25° N to 40° N. Occasional occurrences in the transition region are believed to reflect central-water influence.

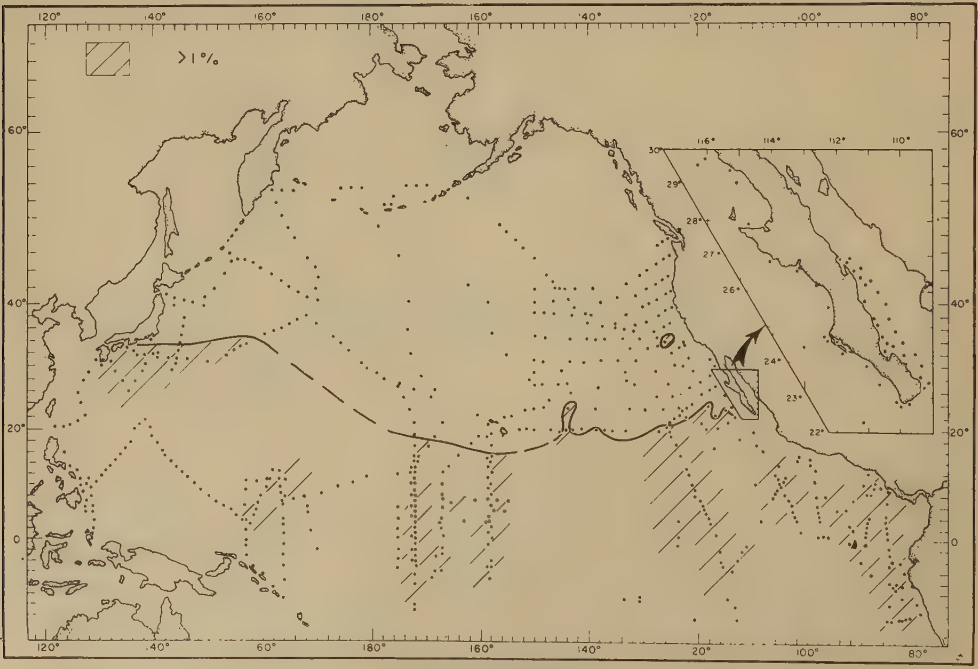
Globigerina pachyderma (Ehrenberg)

Plate 6, figures 20-23

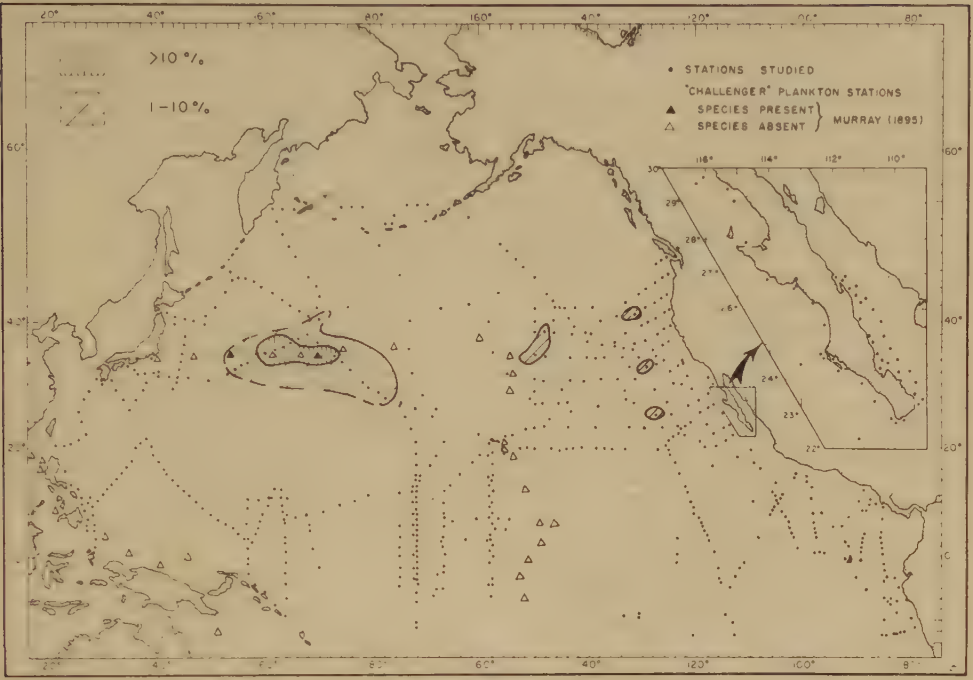
Aristerospira pachyderma EHRENBERG, 1861, Monats. k. preuss. Ak., Wiss. Berlin, p. 303; 1872 (1873), Abhandl. Ak. k. Wiss. Berlin, pl. 1, fig. 4.

This species is sometimes difficult to separate from small specimens of *G. bulloides* but generally may be distinguished by its characteristic crystalline wall structure and constricted aperture.

This species (Text fig. 13) is found in the cold waters of the Subarctic Water mass north of Lat. 40° N and occasionally in the California Current and off northern Japan.



TEXT FIGURE 11
Distribution of *Globigerina hexagona* Natland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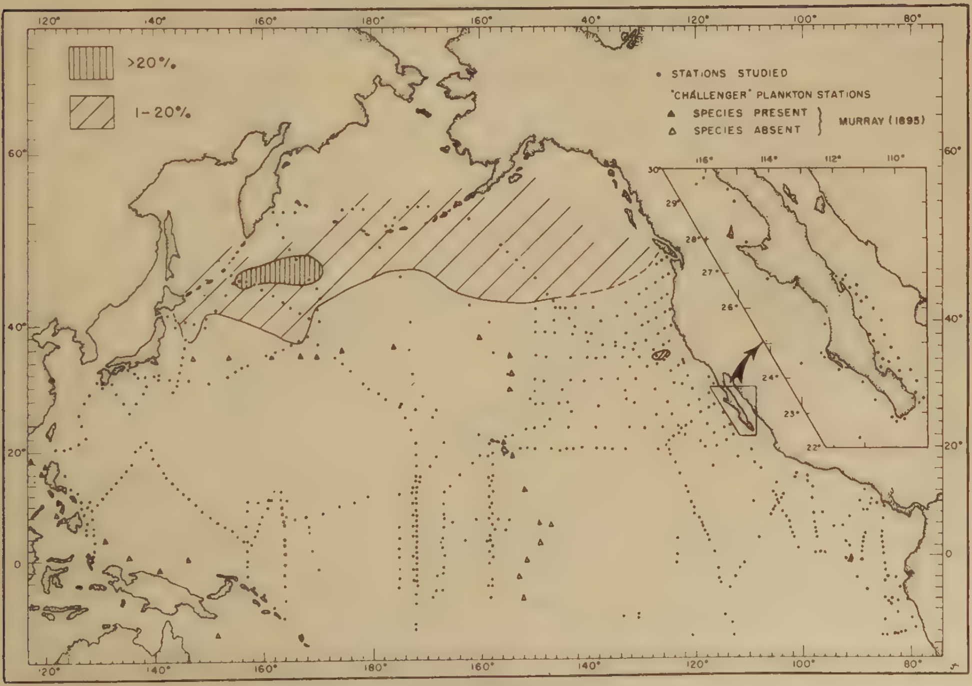
TEXT FIGURE 12
Distribution of *Globigerina inflata* d'Orbigny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TEXT FIGURE 13
Distribution of *Globigerina pachyderma* (Ehrenberg)

Globigerina quinqueloba Natland

Plate 6, figures 24, 25

Globigerina quinqueloba Natland, 1938, Bull. Scripps Inst. Oceanography, Tech. Ser., vol. 4, no. 5, p. 149, pl. 6, fig. 7.

Typical specimens have an extension of the last chamber overlapping the umbilical area. In cold water many small spinose specimens without this overlapping chamber are found. These occur with specimens of typical *G. quinqueloba* and are considered to represent immature stages.

This is the first recorded occurrence of this species from plankton tows. It is common in the cold waters of the subarctic region north of Lat. 40° N (Text fig. 14). It is also found in the transition region represented by the water of the California and Peru currents. Some scattered occurrences are found along the equator.

Globigerina sp.

Plate 6, figures 19, 26-28

Test trochoid; 4-5 chambers in last whorl, earlier chambers small and regular, later ones rapidly becoming elongate; aperture sunken and partially covered by later chambers.

This species has certain similarities to both *G. bulloides* and *Globigerinella aequilateralis* and has probably been included by authors with these species. It is similar to *G. bulloides* in having 4 to 5 chambers in the last whorl but may be distinguished by its less conspicuous, compressed aperture. It may be differentiated from non-planispiral specimens of *Globigerinella aequilateralis* by the smaller number of more elongate chambers.

Globigerina sp. (Text fig. 15) occurs at scattered localities throughout the tropical Pacific.

Globigerinella aequilateralis (Brady)

Plate 7, figures 1, 2

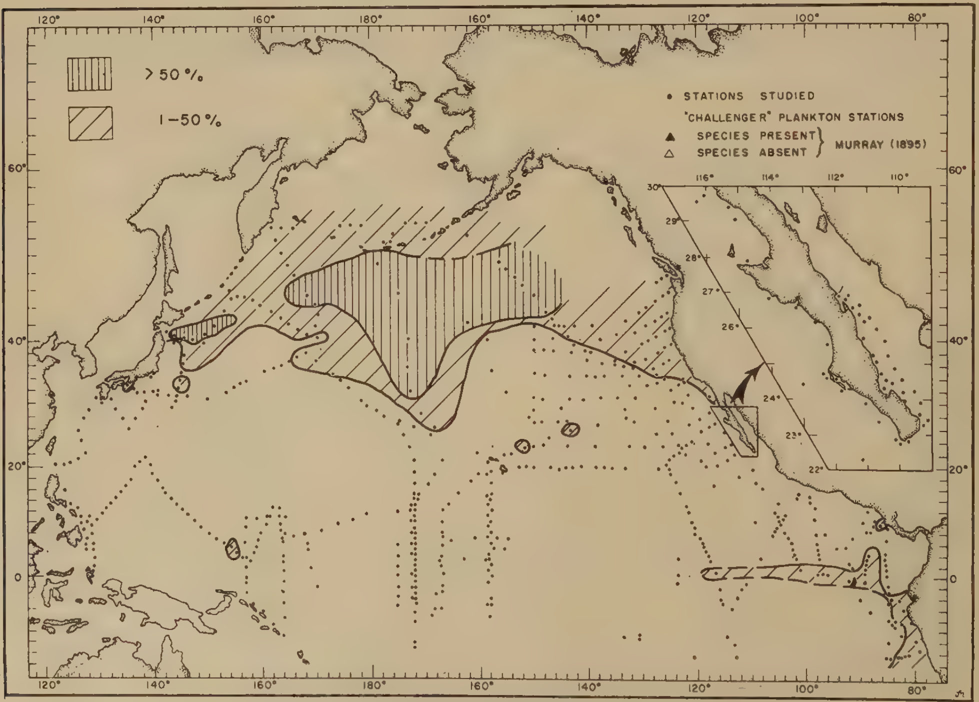
Globigerina aequilateralis Brady, 1879, Quart. Jour. Micr. Sci., vol. 19, p. 71; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 605, pl. 80, figs. 18-21.

This species (Text fig. 16) is most abundant in the tropical and warm-temperate regions. The highest frequencies occur in the equatorial Pacific.

Globigerinella sp.

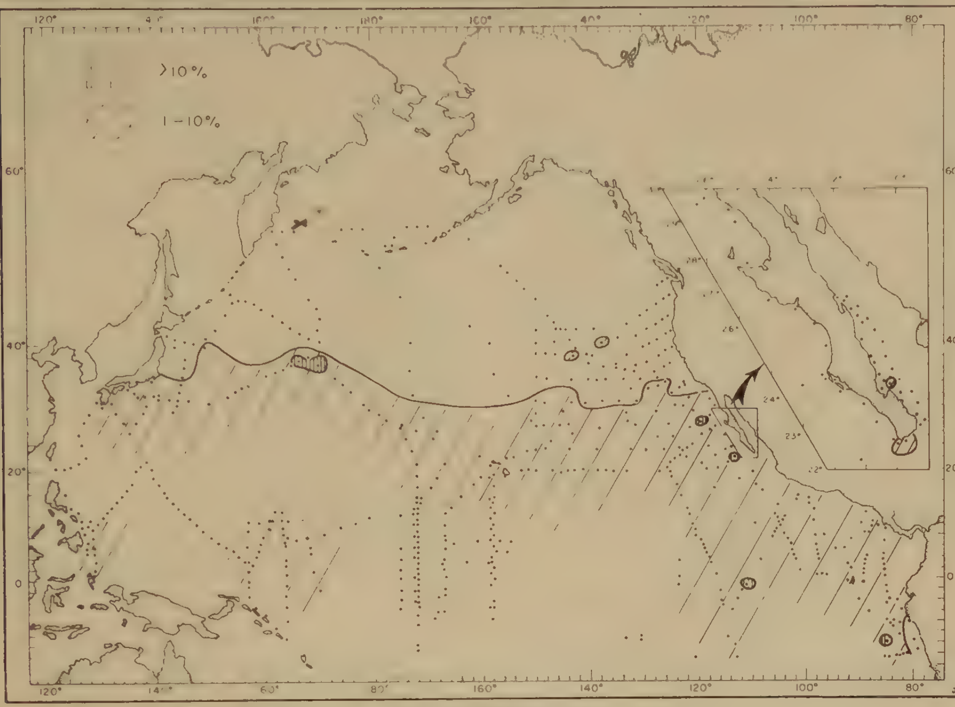
Plate 7, figures 3, 4

Globigerina digitata Brady (part), 1879, Quart. Jour. Micr. Sci., vol. 19, p. 72; 1884 (part), Rept. Voy.



TEXT FIGURE 14

Distribution of *Globigerina quinqueloba* Natland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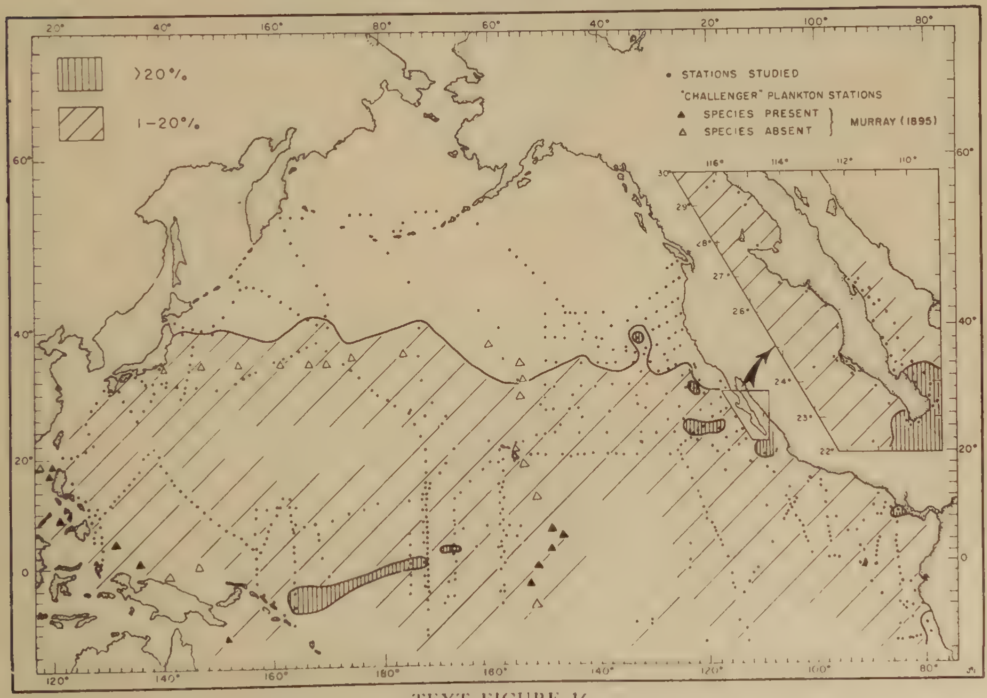
TEXT FIGURE 15
Distribution of *Globigerina* sp.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29°
28°
27°
26°
24°
23°
22°

TEXT FIGURE 16
Distribution of *Globigerinella aequilateralis* (Brady)

CHALLENGER, Zool., vol. 9, p. 599, pl. 82, figs. 6, 7 (not pl. 80, figs. 6-10).

Parker (1958) states that the form described by Brady includes two distinct species. Brady (1884, pl. 82, figs. 6, 7) has illustrated a planispiral form which he describes as being "radiate in a palmate manner" and a trochoid form (Pl. 80, figs. 6-10) which "resembles an outstretched index finger." Parker has designated the trochoid form, which is worldwide, as *Globigerina digitata*. The planispiral one she refers to the genus *Globigerinella*. The latter form is most frequent in Pacific plankton tows while the trochoid species is only rarely observed. In this study the distribution of *Globigerinella* sp. also includes rare occurrences of *Globigerina digitata*.

Highest concentrations of *Globigerinella* sp. (Text fig. 17) are found in the equatorial Pacific region. Significant frequencies also occur in waters of the Kuroshio in the west-central Pacific.

Globigerinita glutinata (Egger)

Plate 7, figures 7, 8

Globigerina glutinata Egger, 1893, Abhandl. K. bay. Akad. Wiss. Munchen, Cl. II, vol. 18, p. 371, pl. 13, figs. 19-21.—Rhumbler, 1911, Ergeb. Plankton-Exped. Humboldt Stift., vol. 3, p. 148, pl. 29, figs. 14-26; pl. 33, fig. 20; pl. 34, fig. 1.

This species (Text fig. 18) is most abundant in the tropical regions but it (or a closely related form) also ranges into the subarctic water. The colder-water specimens are smaller than those from the tropics.

Globigerinoides conglobata (Brady)

Plate 7, figures 5, 6

Globigerina conglobata Brady, 1879, Quart. Jour. Micr. Sci., vol. 19, p. 72; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 603, pl. 80, figs. 1-5; pl. 82, fig. 5.

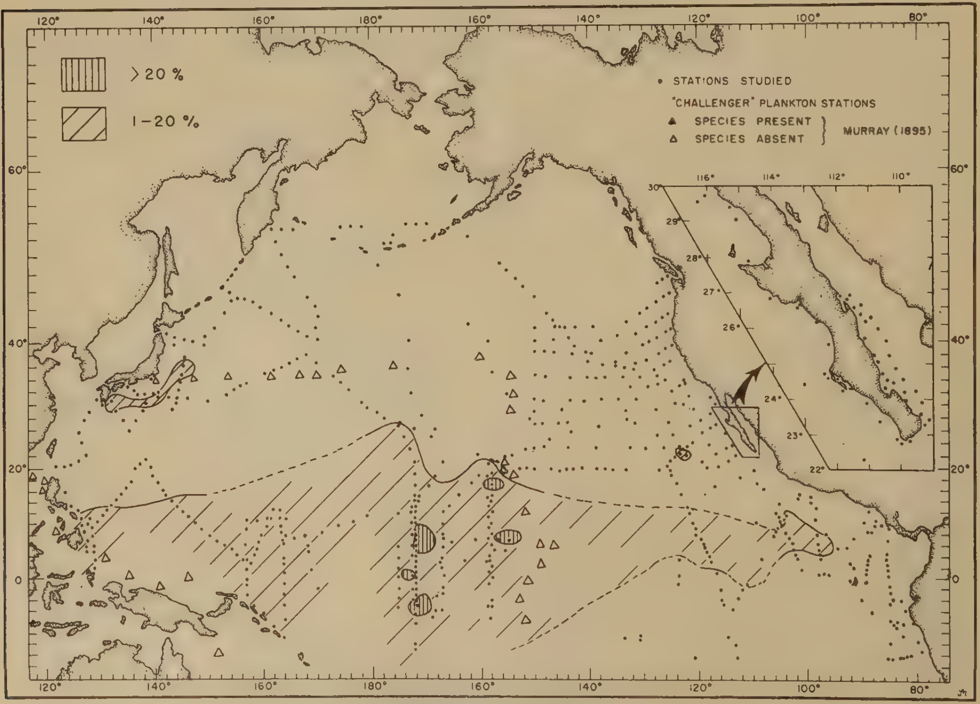
Large adult specimens of this species have a very massive and compact appearance. The primary aperture consists of a narrow arched opening on the ventral surface. Accessory apertures are present along the sutures on the dorsal side. Younger specimens are usually less compact and the aperture is larger and more distinct. These immature forms are very similar to specimens of *Globigerinoides* sp. and are difficult to distinguish from that species.

This species (Text fig. 19), which is limited to the warm-water region, has its greatest abundance in the equatorial Pacific.

Globigerinoides cf. G. minuta Natland

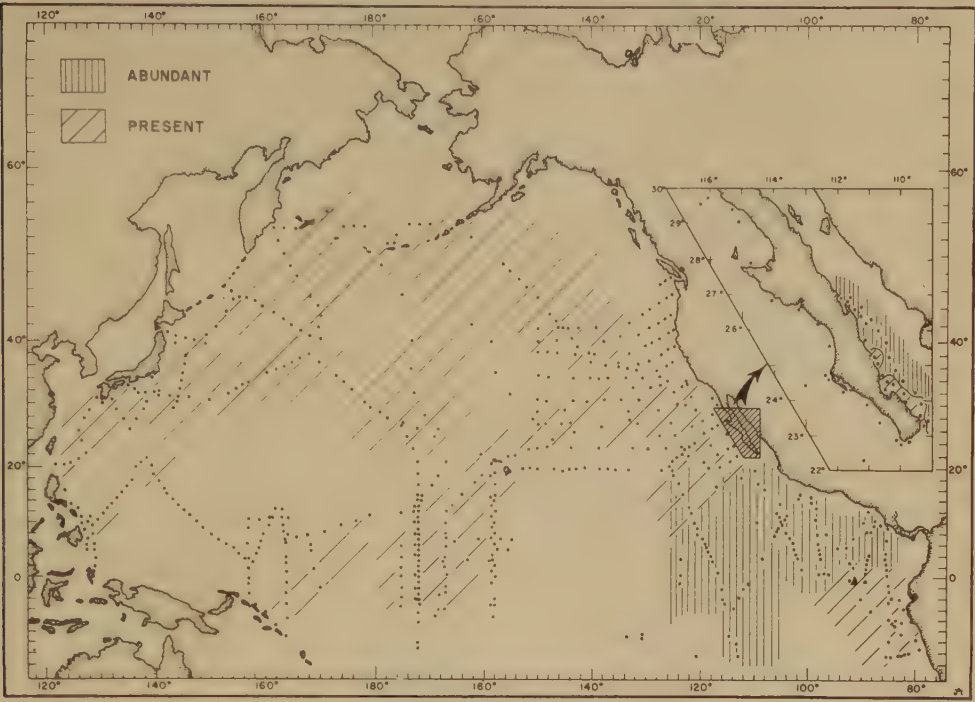
Plate 7, figures 9-11

This form is closely related to Natland's (1938)



TEXT FIGURE 17

Distribution of *Globigerinella* sp.


ABUNDANT
PRESENT
120°
140°
160°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0
116°
114°
112°
110°
30°
29°
28°
27°
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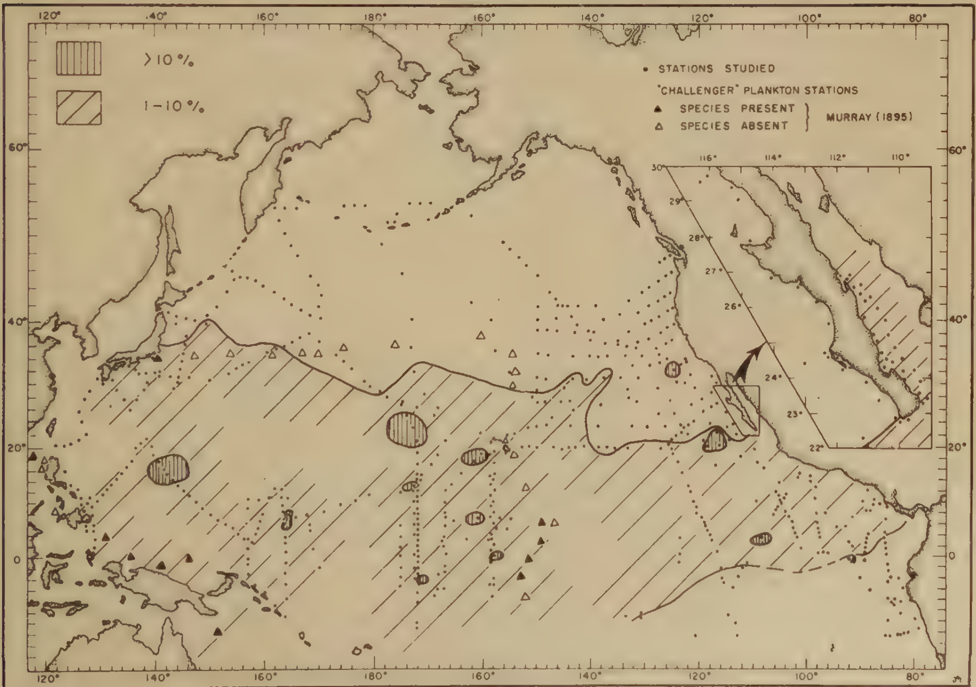
24°
23°
22°

TEXT FIGURE 18
Distribution of *Globigerinita glutinata* (Egger)


>10%
1-10%
• STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
▲ SPECIES PRESENT
△ SPECIES ABSENT
MURRAY (1895)
120°
140°
160°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0
116°
114°
112°
110°
30°
29°
28°
27°
26°
24°
23°
22°

TEXT FIGURE 19
Distribution of *Globigerinoides conglobata* (Brady)

species but has a slightly more spinose surface. Accessory apertures are present. Immature stages are difficult to separate from juvenile specimens of *Globigerinita glutinata* that occur with them; adult specimens may be differentiated by their relatively higher spires when compared with equal sized individuals of the latter species.

This species (Text fig. 20) is most abundant in the subarctic region but occasionally occurs in the temperate zone.

Globigerinoides rubra (d'Orbigny)

Plate 7, figures 12, 13

Globigerina rubra D'ORBIGNY, 1839, *in* DE LA SAGRA, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 82, pl. 4, figs. 12-14.

This species (Text fig. 21) is found throughout the tropical and temperate regions of the Pacific. Highest frequencies occur in equatorial waters but considerable numbers also are found within the transition zone. The greatest concentrations (up to 2,586/1,000 m^3) are recorded in the Gulf of California.

Globigerinoides sacculifera (Brady)

Plate 7, figures 14, 15, 18

Globigerina sacculifera BRADY, 1877, Geol. Mag., vol. 4, p. 535; 1879, Quart. Jour. Micr. Sci., vol. 19, p. 73; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 604, pl. 80, figs. 11-17; pl. 82, fig. 4.

Specimens of this species do not always have the characteristic elongated final chamber. Some authors have considered such sac-less specimens to be a separate species (*Globigerina triloba* Reuss), and others (for instance, Cushman, 1914, pl. 2, figs. 7, 8, 9) have referred them to *Globigerina bulloides*.

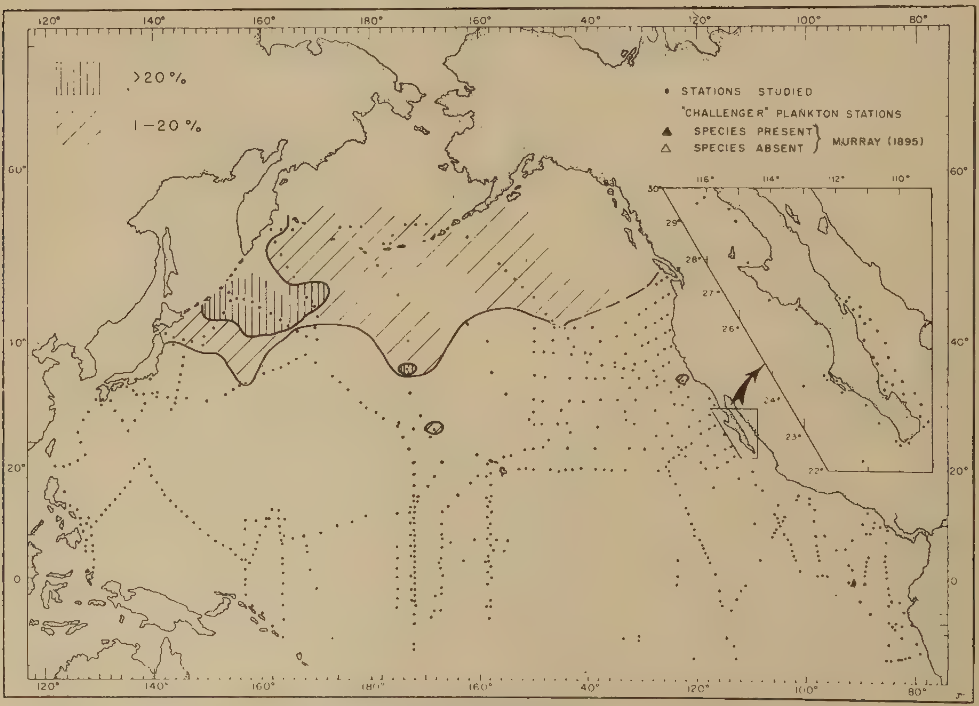
This species (Text fig. 22) is restricted to the warm regions, reaching its maximum frequency in the equatorial Pacific.

Globigerinoides sp.

Plate 7, figures 16, 17

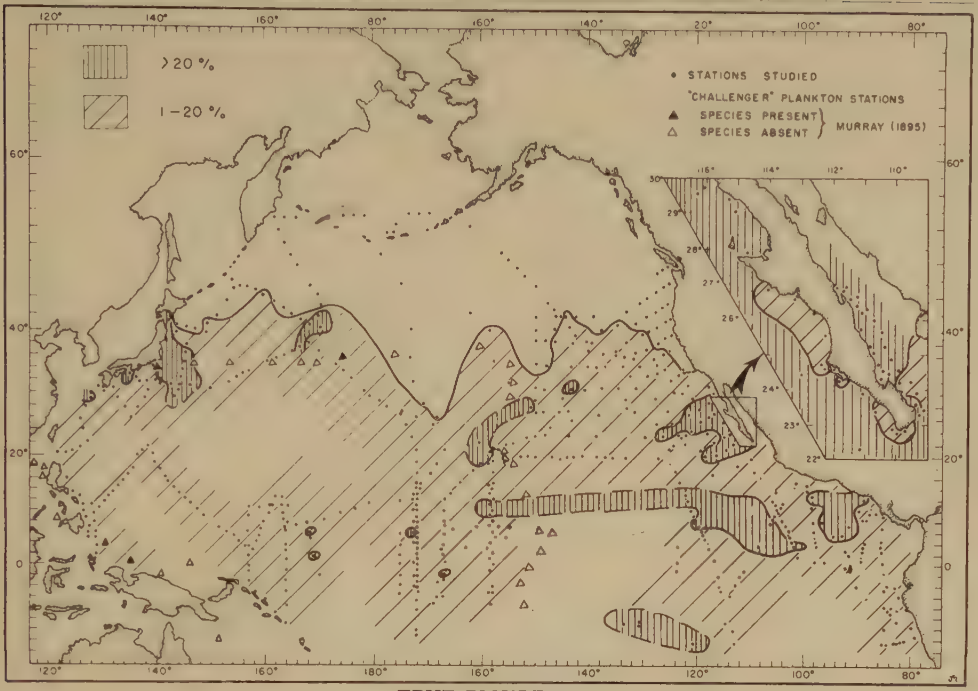
Test trochoid, rotaliform; 4 chambers in last whorl, large and inflated, gradually increasing in size; primary aperture a large arched opening with several secondary apertures located in the sutural depressions on the dorsal side; walls coarsely perforate and spinose.

This form is somewhat similar to *G. rubra* and *Globigerina bulloides*. It may be distinguished from the former in having four chambers in the final whorl and smaller accessory apertures. The accessory apertures distinguish it from *G. bulloides*. There is a possibility that this form is a variant of *Globigerinoides conglobata*.



TEXT FIGURE 20

Distribution of *Globigerinoides* cf. *G. minuta* Natland


>20 %
1–20 %
• STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
▲ SPECIES PRESENT
△ SPECIES ABSENT
MURRAY (1895)
120°
140°
160°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0
116°
114°
112°
110°
30°
29°
28°
27°
26°
24°
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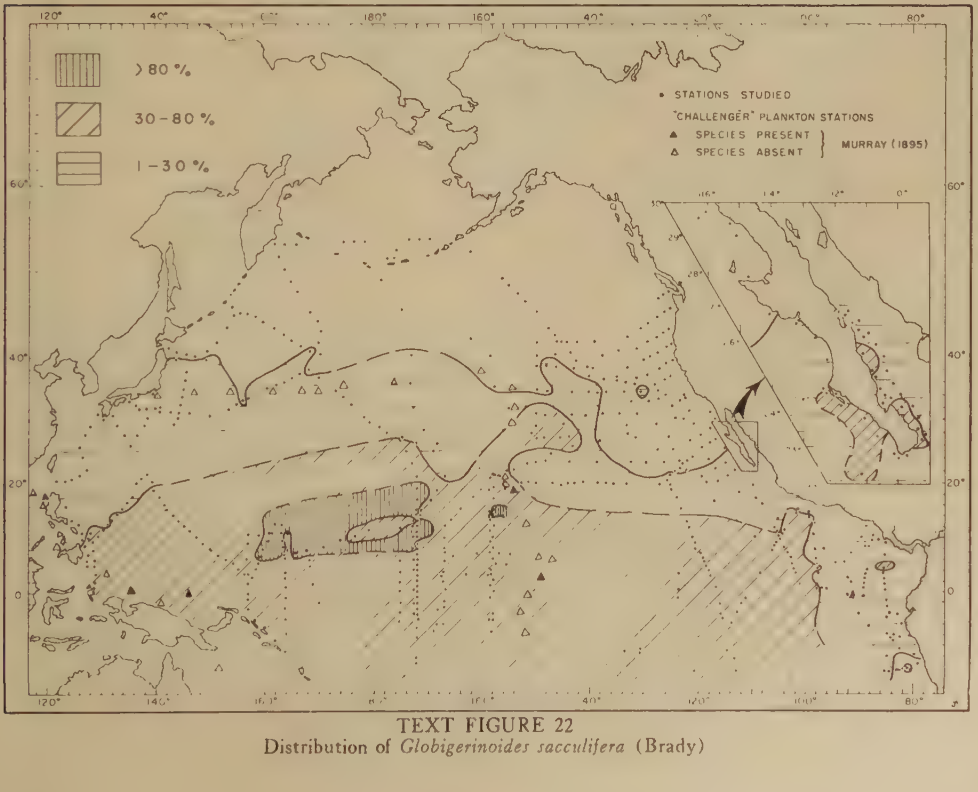
22°

TEXT FIGURE 21
Distribution of *Globigerinoides rubra* (d'Orbigny)


>80 %
30–80 %
1–30 %
• STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
▲ SPECIES PRESENT
△ SPECIES ABSENT
MURRAY (1895)
120°
140°
160°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0
30°
29°
28°

TEXT FIGURE 22
Distribution of *Globigerinoides sacculifera* (Brady)

This species (Text fig. 23) is found throughout the tropical and temperate regions of the Pacific.

Globorotalia hirsuta (d'Orbigny)

Plate 8, figures 1, 2

Rotalina hirsuta d'Orbigny, 1839, *in* Barker-Webb and Berthelot, Hist. Nat. Îles Canaries, vol. 2, pt. 2, "Foraminifères," p. 131, pl. 1, figs. 37-39.

Pulvinulina canariensis Brady (not d'Orbigny, 1839), 1844, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 692, pl. 103, figs. 8-10.

Globorotalia hirsuta (d'Orbigny). Cushman, 1931, Bull. 104, U. S. Nat. Mus., pt. 8, p. 99, pl. 17, fig. 6.

This species (Text fig. 24) occurs at widely scattered localities throughout the tropical and warm-temperate regions, being more abundant in the former.

Globorotalia menardii (d'Orbigny)

Plate 8, figures 3, 4

Rotalia menardii d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 273, no. 26; Modèles, no. 10.

Pulvinulina menardii (d'Orbigny). Brady, 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 690, pl. 103, figs. 1, 2.

This species may be distinguished from *G. tumida* by its flattened shape and lack of a visibly crystalline wall structure. Plate 8, figures 10-12 show an intergrade which has been included with *G. menardii.*

This species (Text fig. 25) is found only in the tropical and warm-temperate zones. Its greatest frequencies are in the equatorial regions.

Globorotalia scitula (Brady)

Plate 8, figures 5, 6

Pulvinulina scitula Brady, 1882, Proc. Roy. Soc. Edinburgh, vol. 11, p. 716.

Pulvinulina patagonica Brady (not d'Orbigny, 1839), 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 693, pl. 103, fig. 7.

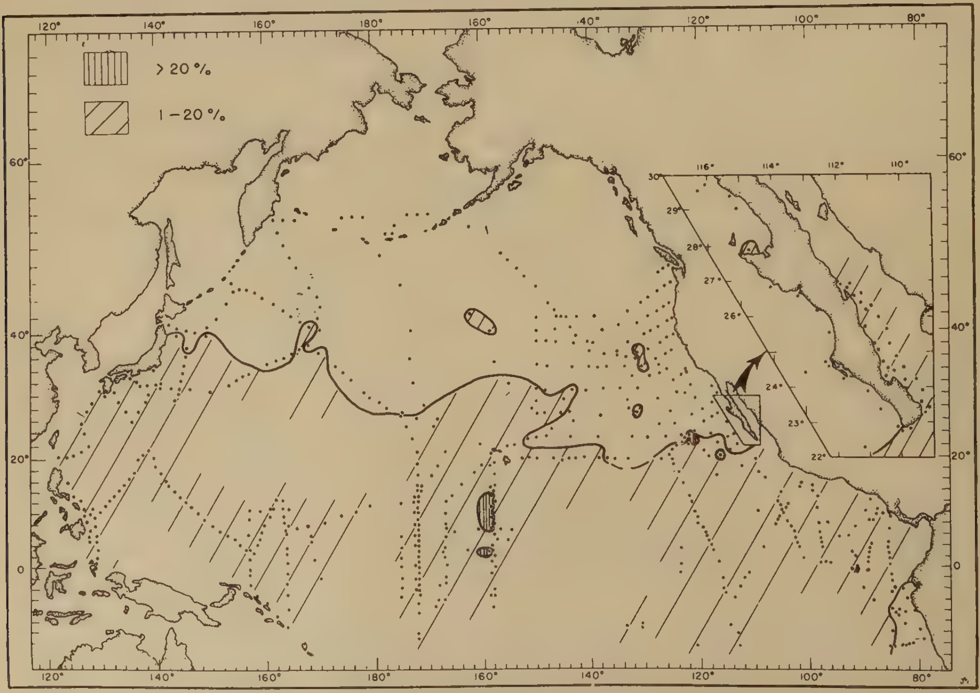
This species (Text fig. 26) is widely distributed throughout the North Pacific. High concentrations are found off the coast of Washington in the cold waters of the California Current. There are scattered occurrences near the boundary of the Kuroshio and Oyashio, in the Peru Current, and in the equatorial Pacific.

Globorotalia truncatulinoides (d'Orbigny)

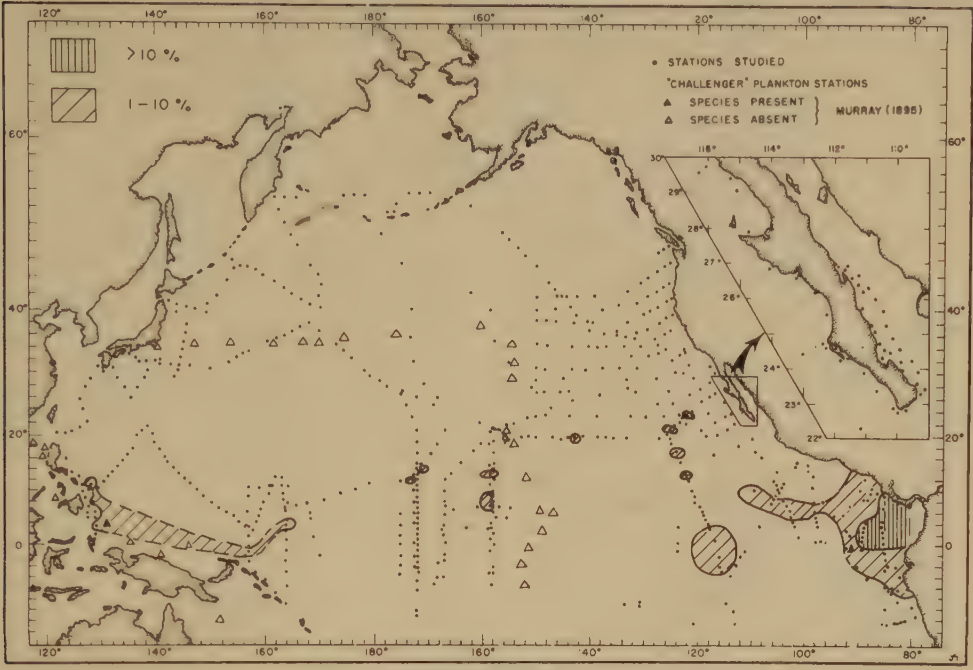
Plate 8, figures 7, 8

Rotalina truncatulinoides d'Orbigny, 1839, *in* Barker-Webb and Berthelot, Hist. Nat. Îles Canaries, vol. 2, pt. 2, "Foraminifères," p. 132, pl. 2, figs. 25-27.

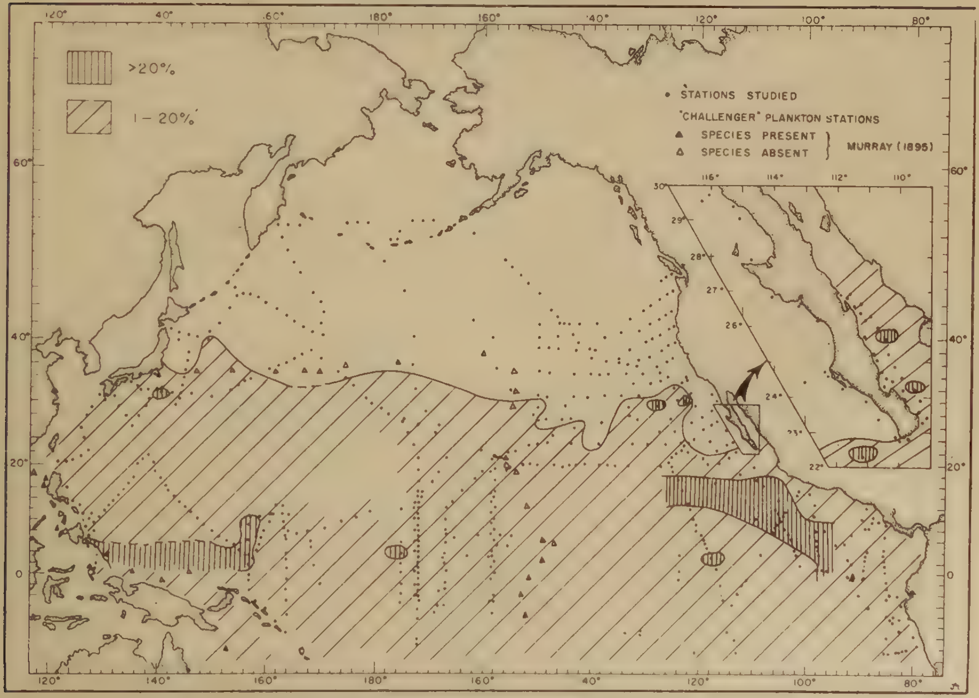
Pulvinulina michelineana Brady (not d'Orbigny,



TEXT FIGURE 23
Distribution of *Globigerinoides* sp.


>10 %
1–10 %
• STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
▲ SPECIES PRESENT
△ SPECIES ABSENT
MURRAY (1895)
120° 140° 160° 180° 160° 140° 120° 100° 80°
60° 40° 20° 0
116° 114° 112° 110°
30° 29° 28° 27° 26° 24° 23° 22°

TEXT FIGURE 24
Distribution of *Globorotalia hirsuta* (d'Orbigny)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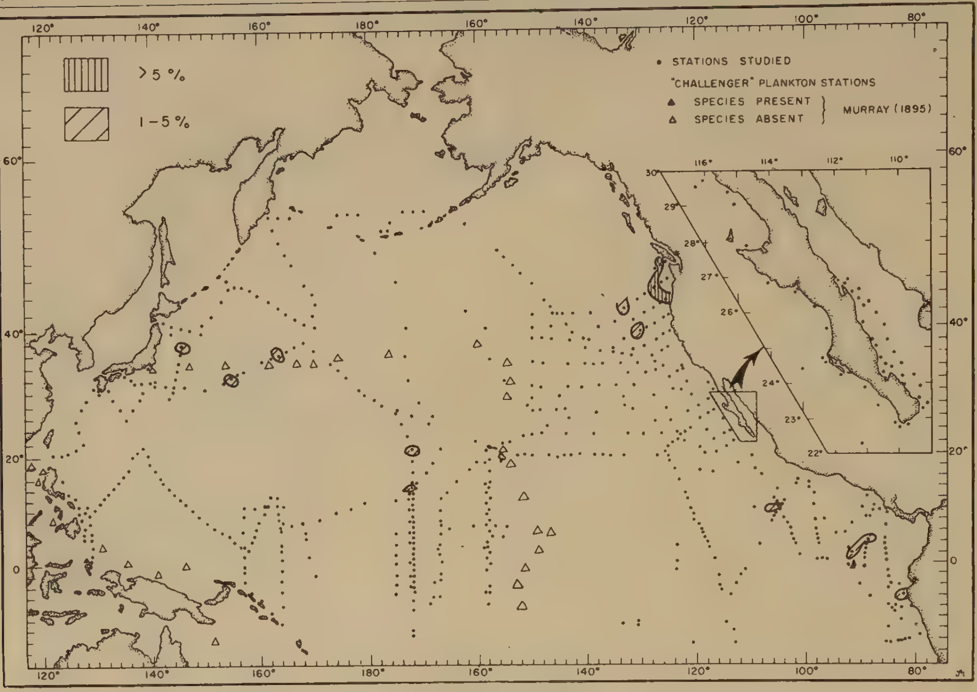
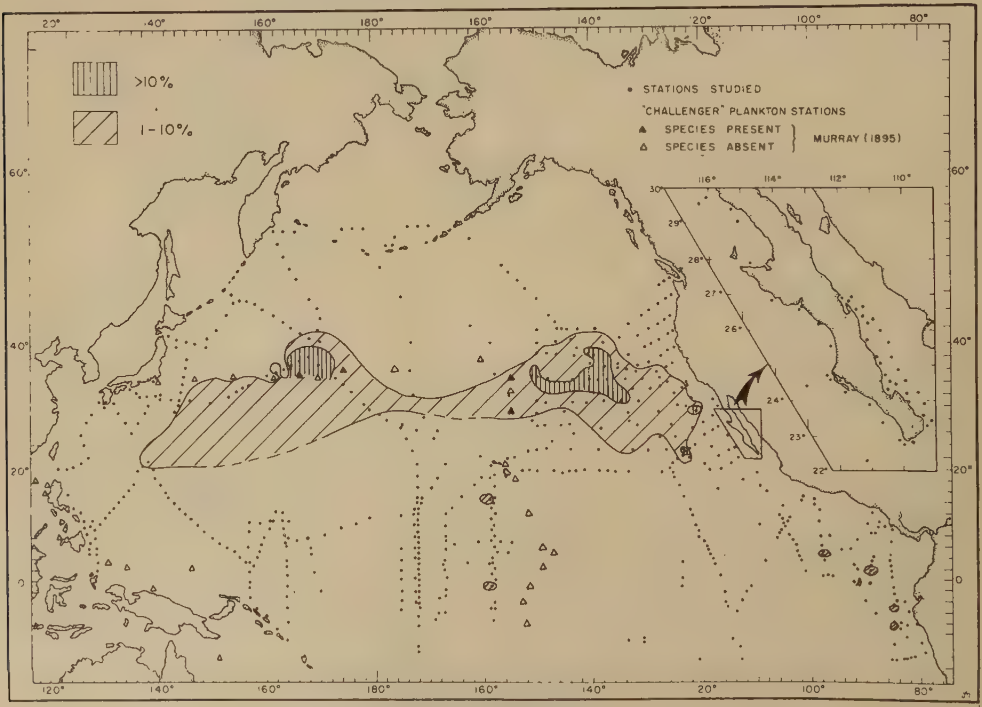
1–20%
• STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
▲ SPECIES PRESENT
△ SPECIES ABSENT
MURRAY (1895)
120° 140° 160° 180° 160° 140° 120° 100° 80°
60° 40° 20° 0
116° 114° 112° 110°
30° 29° 28° 27° 26° 24° 23° 22°

TEXT FIGURE 25
Distribution of *Globorotalia menardii* (d'Orbigny)


>5 %
1-5 %
STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
SPECIES PRESENT
SPECIES ABSENT
MURRAY (1895)
120° 140° 160° 180° 160° 140° 120° 100° 80°
60° 40° 20° 0
116° 114° 112° 110°
30° 29° 28° 27° 26° 24° 23° 22°

TEXT FIGURE 26
Distribution of *Globorotalia scitula* (Brady)


>10%
1-10%
STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
SPECIES PRESENT
SPECIES ABSENT
MURRAY (1895)
120° 140° 160° 180° 160° 140° 120° 100° 80°
60° 40° 20° 0
116° 114° 112° 110°
30° 29° 28° 27° 26° 24° 23° 22°

TEXT FIGURE 27
Distribution of *Globorotalia truncatulinoides* (d'Orbigny)

1840), 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 694, pl. 104, figs. 1, 2.

This species (Text fig. 27) is most abundant in a relatively narrow band extending across the North Pacific from approximately 40° N Lat. to 20° N Lat. It is also recorded at low frequencies from three stations along the equator and from one station approximately 5° south of Hawaii. The highest concentration occurs in the Western Central Water mass at the boundary of the warm Kuroshio and the cold Oyashio currents. Like *Globigerina inflata* it appears to be primarily a central-water species that is occasionally found in the transition region.

It is of interest that *Globorotalia truncatulinoides* occurs in approximately similar latitudinal ranges in both the North and South Pacific.

Globorotalia tumida (Brady)

Plate 8, figures 9, 13

Pulvinulina menardii D'ORBIGNY var. *tumida* BRADY, 1877, Geol. Mag., vol. 4, p. 294.

Pulvinulina tumida BRADY, 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 692, pl. 103, figs. 4-6.

This form is separated from *G. menardii* by its more tumid form and the crystalline nature of its wall.

This species (Text fig. 28) is found only in the tropical regions. It appears to be less tolerant of cold temperatures than *G. menardii* and is not found as far north as that species. The highest concentrations of *G. tumida* occur nearer the equator and farther west than the greatest abundance of *G. menardii*.

Hastigerina pelagica (d'Orbigny)

Plate 8, figures 14, 15

Nonionina pelagica D'ORBIGNY, 1839, Foram. Amér. Mérid., p. 27, pl. 3, figs. 13, 14.

Hastigerina pelagica (D'ORBIGNY). BRADY, 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 613, pl. 83, figs. 1-8.

This species (Text fig. 29) is found widely distributed in the tropical and warm-temperate regions. The greatest concentrations occur in the central oceanic regions. More than 700 specimens per 1000 m³ occur near Hawaii.

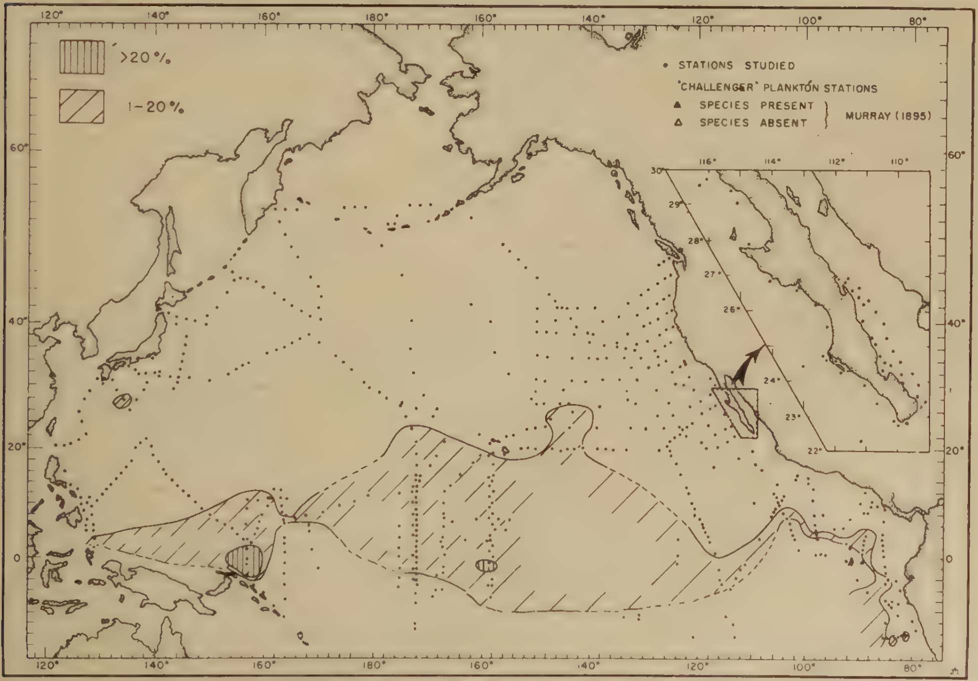
Hastigerinella rhumbleri Galloway

Plate 8, figure 16

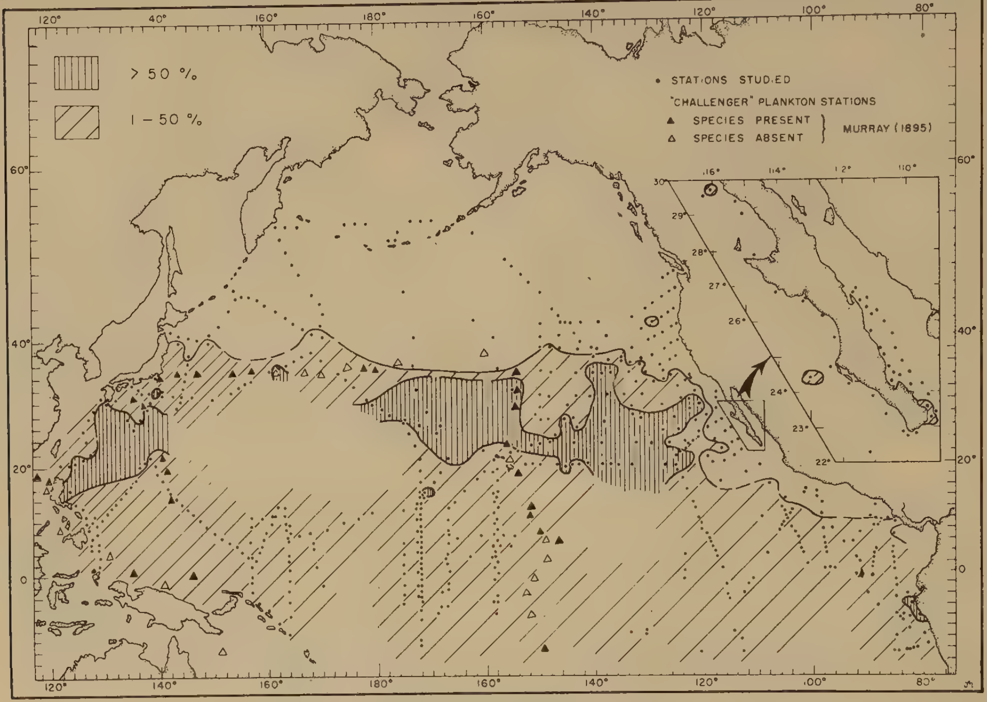
Hastigerina digitata RHUMBLER (not *Globigerina digitata* BRADY), 1911, Ergeb. Plankton-Exped. Humboldt Stift., vol. 3, pt. 1, p. 202, pl. 37, fig. 9.

Hastigerinella digitata (RHUMBLER). WIESNER, 1931, Deutsche Sud-Polar Exped., vol. 20, Zool., p. 135, pl. 22, figs. 264-266.

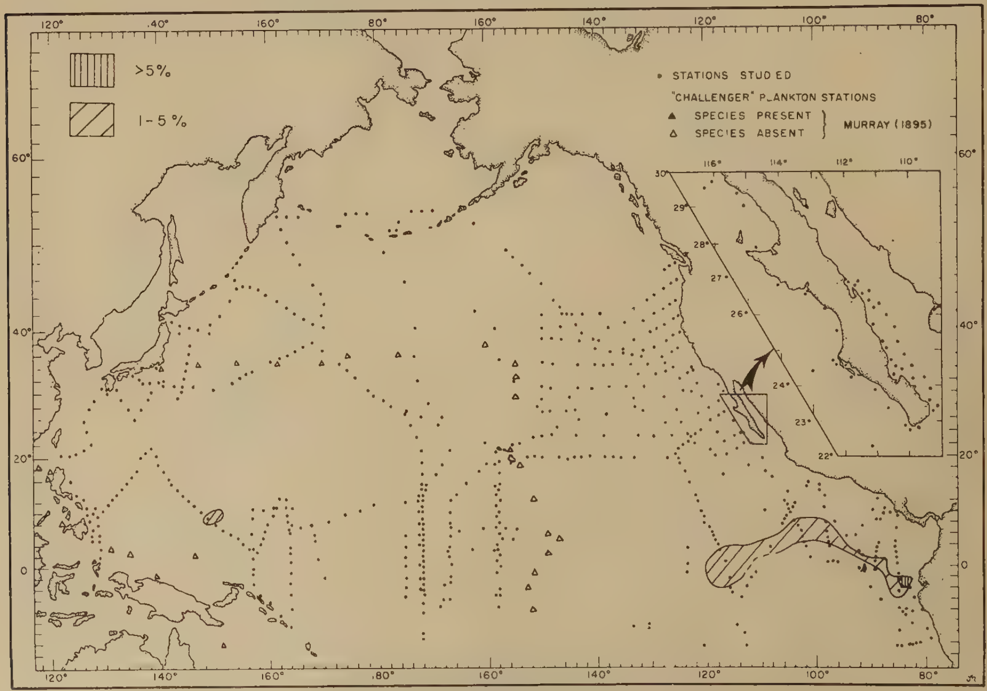
Hastigerinella rhumbleri GALLOWAY, 1933, A Manual



TEXT FIGURE 28
Distribution of *Globorotalia tumida* (Brady)


> 50 %
1 – 50 %
• STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
▲ SPECIES PRESENT
△ SPECIES ABSENT
MURRAY (1895)
120° 140° 160° 180° 160° 140° 120° 100° 80°
60° 40° 20° 0
116° 114° 112° 110°
30° 29° 28° 27° 26° 24° 23° 22°

TEXT FIGURE 29
Distribution of *Hastigerina pelagica* (d'Orbigny)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1-5 %
• STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
▲ SPECIES PRESENT
△ SPECIES ABSENT
MURRAY (1895)
120° 140° 160° 180° 160° 140° 120° 100° 80°
60° 40° 20° 0
116° 114° 112° 110°
30° 29° 28° 27° 26° 24° 23° 22°

TEXT FIGURE 30
Distribution of *Hastigerinella rhumbleri* Galloway

(84)

of Foraminifera, Bloomington, Ind., p. 333, pl. 30, fig. 9.

This is a very rare and fragile species which probably explains why there are no reports of its presence in bottom sediments. The specimen illustrated by Cushman, Todd and Post (1954, pl. 91, figs. 9, 10) appears to be the *Globigerinella* sp. reported in this study.

Hastigerinella rhumbleri (Text fig. 30) is found in the tropical and temperate regions of the Pacific. It occurs in the upper water layers at 12 stations in the equatorial region, all within 8° of the equator. Two deep occurrences (not shown in the surface distribution in Text fig. 30) lie outside of this region; one from a deep tow at the junction of the Kuroshio and Oyashio currents, the other from a deep open-and-closing haul off San Diego, California.

Orbulina universa d'Orbigny

Plate 8, figures 17, 18

Orbulina universa d'Orbigny, 1839, *in* De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 3, pl. 1, fig. 1.

Most of the specimens are similar to the type but occasionally bilocular ones are found.

This species (Text fig. 31) is very widely distributed in the tropical and temperate regions. The highest concentration is recorded near Hawaii but high numbers also were noted within the cool California Current extending northward into the Gulf of Alaska, along the equator, and near the boundary of the Kuroshio and Oyashio currents.

Pulleniatina obliquiloculata (Parker and Jones)

Plate 8, figures 19, 20

Pullenia obliquiloculata Parker and Jones, 1865, Philos. Trans., vol. 155, p. 368, pl. 19, fig. 4.

Immature specimens of this species do not have the crescent-shaped aperture characteristic of the adult and are more lobate and coarsely perforate.

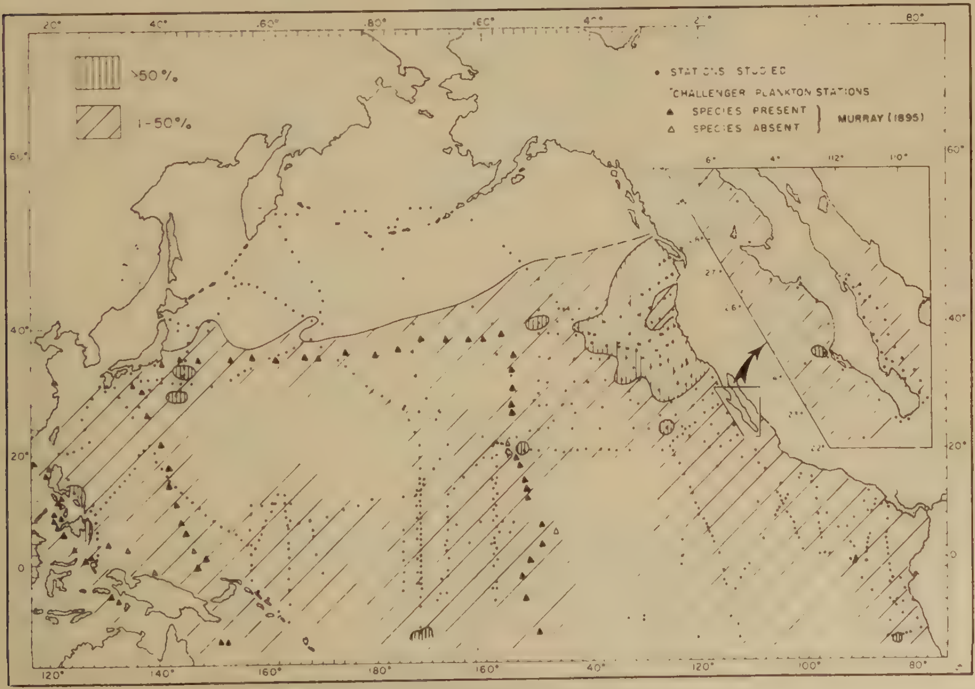
This species (Text fig. 32) is most common in the tropical region. The area of maximum abundance (> 1000 specimens/1000 m^3) lies in the center of the Pacific Equatorial Water mass south of Hawaii. The concentrations appear to diminish to the east and west.

Sphaeroidinella dehiscens (Parker and Jones)

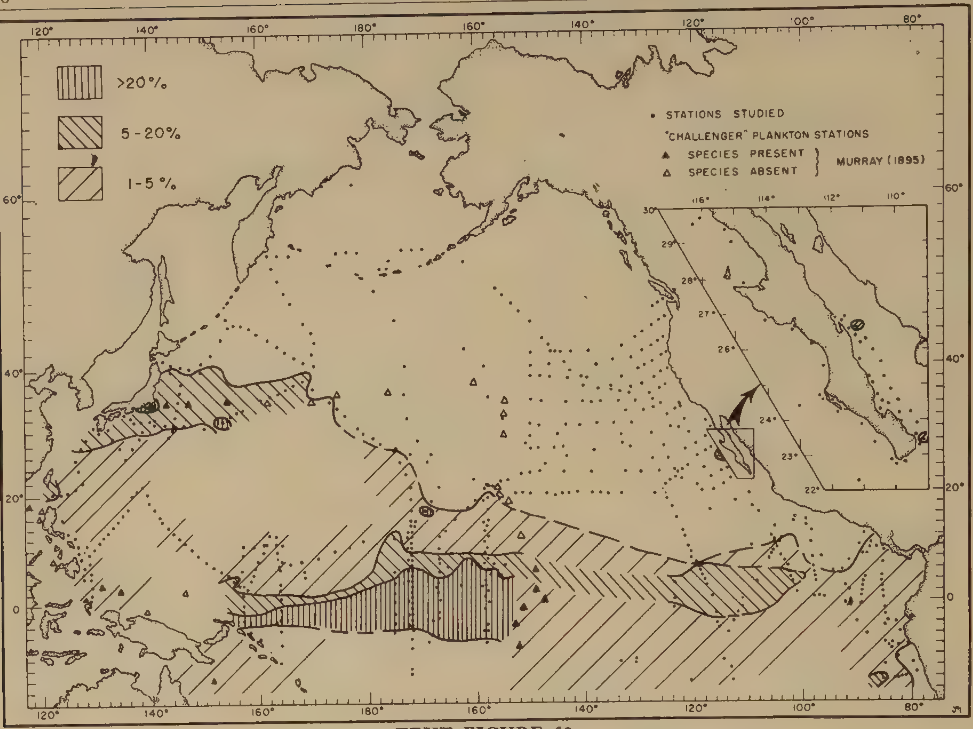
Plate 8, figures 21-23

Sphaeroidina dehiscens Parker and Jones, 1865, Philos. Trans., vol. 155, p. 369, pl. 19, fig. 5.

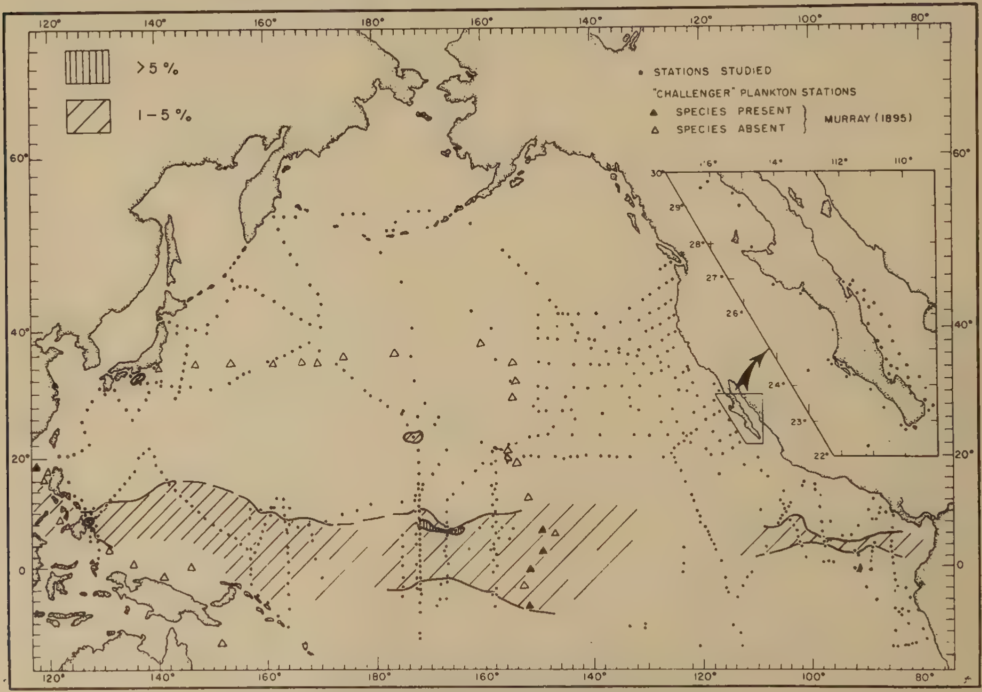
S. dehiscens (Text fig. 33) is most abundant in the center of the equatorial Pacific region. To the east and west the frequencies become lower. One occurrence is recorded from the Kuroshio off southern Japan.



TEXT FIGURE 31
Distribution of *Orbulina universa* d'Orbigny


>20%
5-20%
1-5%
• STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
▲ SPECIES PRESENT
△ SPECIES ABSENT
MURRAY (1895)
120° 140° 160° 180° 160° 140° 120° 100° 80°
60° 40° 20° 0
116° 114° 112° 110°
30° 29° 28° 27° 26° 24° 23° 22°

TEXT FIGURE 32
Distribution of *Pulleniatina obliquiloculata* (Parker and Jones)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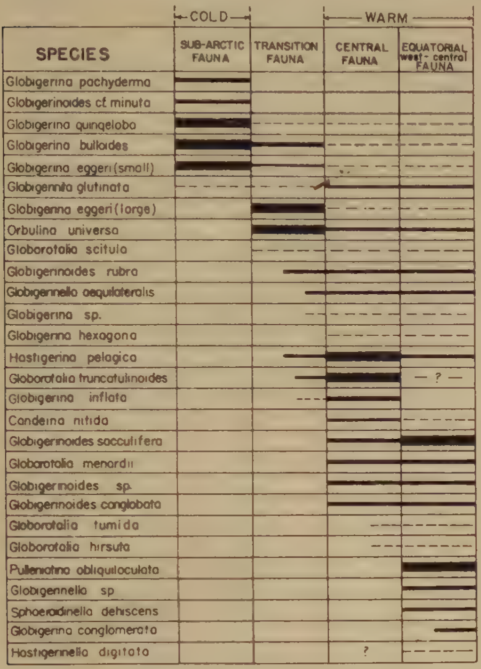
• STATIONS STUDIED
"CHALLENGER" PLANKTON STATIONS
▲ SPECIES PRESENT
△ SPECIES ABSENT
MURRAY (1895)
120° 140° 160° 180° 160° 140° 120° 100° 80°
60° 40° 20° 0
116° 114° 112° 110°
30° 29° 28° 27° 26° 24° 23° 22°

TEXT FIGURE 33
Distribution of *Sphaeroidinella dehiscens* (Parker and Jones)



TEXT FIGURE 34

Generalized ranges of species

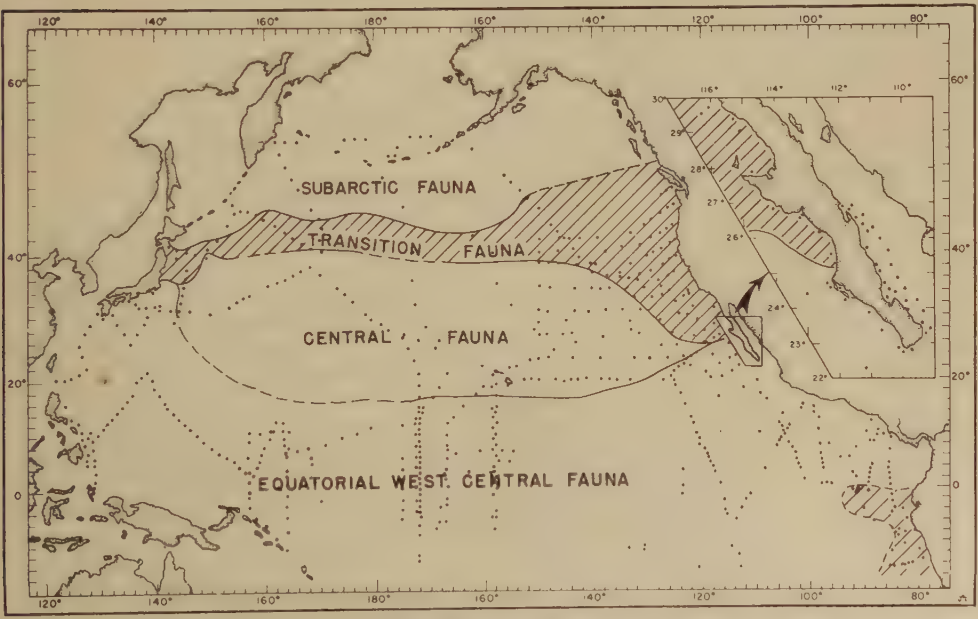
DISTRIBUTION OF PLANKTONIC FORAMINIFERA IN THE PACIFIC

Geographic Distribution of Faunas

Distributions of species in the surface water of the North and equatorial Pacific (Text figs. 7-33) may be divided into three general groups, a northern cold-water or subarctic fauna, a southern warm-water fauna, and a transition fauna composed of species of both the cold- and warm-water groups. Species of the warm-water fauna are not uniformly distributed throughout the region and may be further grouped into minor assemblages. In general, these natural groupings based upon the distribution of the species coincide with the geography of the surface water masses as previously described. Text figure 34 shows the generalized ranges of all the species. The geographic extent of the faunas is shown in Text figure 35. The faunal boundaries in the southern hemisphere are hypothetical and have been extrapolated from what is known in the North Pacific.

Cold-water (Subarctic) fauna.—This fauna contains species that are restricted to the subarctic region and also includes a few wide-ranging forms that extend into the warm region to the south. The following species have their highest frequencies in this region: *Globigerina* cf. *"G. dutertrei," G. pachyderma, G. quinqueloba, Globigerinoides* cf. *G. minuta.*

The following forms occur with this fauna, some-



TEXT FIGURE 35

Generalized distribution of faunal assemblages times in high frequency, although they are also found in the transition fauna to the south: *Globigerina bulloides, G. eggeri* (dwarfed forms including specimens referred to "*G. dutertrei*"), *Globigerinita glutinata.*

The northern limit of this group is not known but the occurrence of *Globigerina bulloides* and *G. pachyderma* in sediments of the Beaufort and Chukchi Seas (Carsola, 1952) suggests that at least certain elements of this fauna range well into the arctic region. Phleger (1952) reports these species in sediment samples from the Canadian and Greenland arctic. The southern limit of the fauna approximates the Polar Front, or Subarctic Convergence, found between 40-45° N Lat. Where no distinct front occurs the 15° C summer isotherm marks the southern boundary.

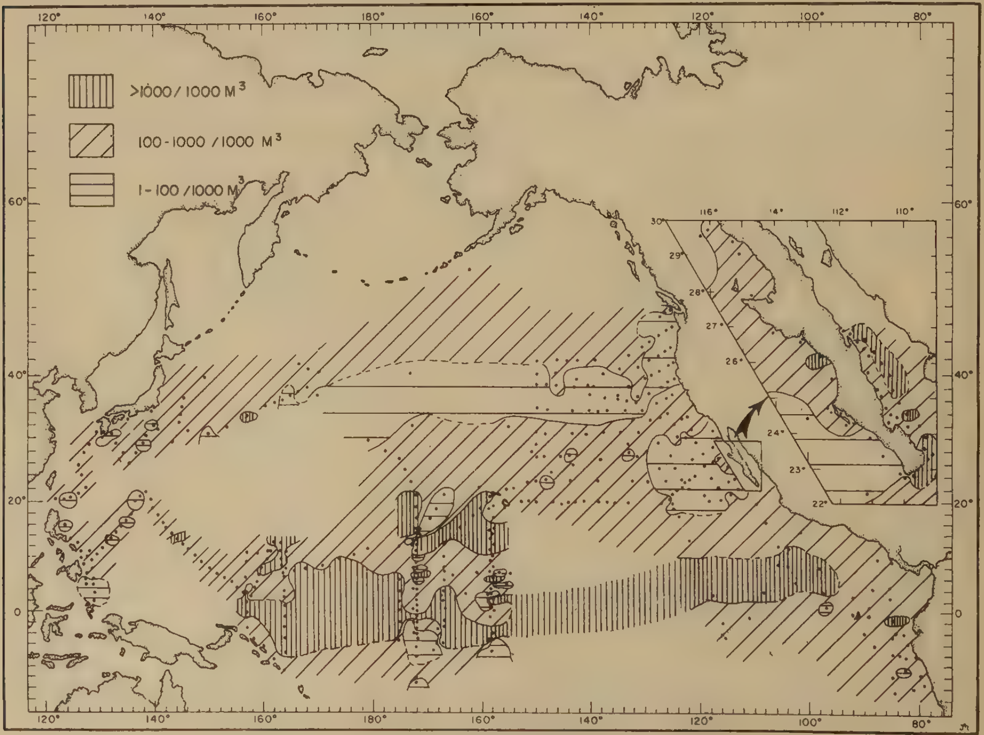
Transition fauna.—Between the subarctic and warm-water regions lies an extensive area of faunal mixing. The characteristic fauna contains elements of both the northern subarctic and the warm-water faunas to the south and west. The species composition varies depending upon the distance from the original faunas and the degree of mixing.

The following species are common in this region: *Globigerina bulloides, G. eggeri* (large specimens), *G. quinqueloba, Globigerinoides rubra, Orbulina universa.*

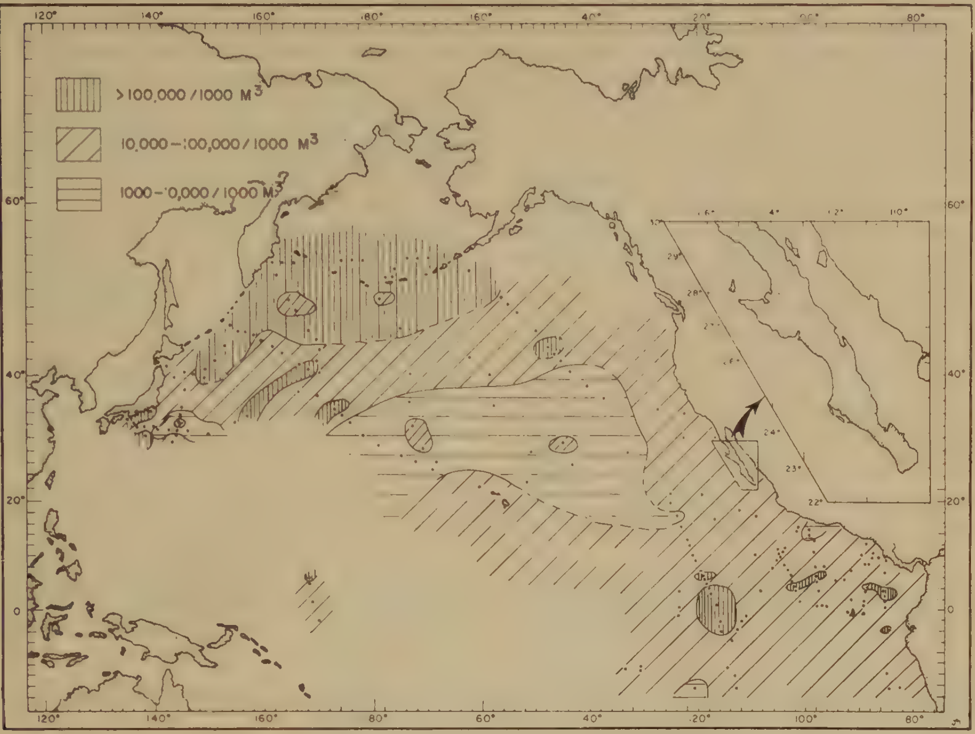
The northern boundary of the transition region is arbitrarily defined as the northern limit of the distribution of *Orbulina universa* and large specimens of *G. eggeri.* The southern boundary is marked by the appearance of equatorial species such as *Globigerinoides sacculifera* and *Globorotalia menardii.*

The 15° C and 20° C summer isotherms are closely associated with these limits to the north and south respectively, the California Current marking part of the boundary in the northeast Pacific. The geographic limits of this region are not fixed but appear to vary in response to seasonal changes. In summer occasional specimens of *Hastigerina pelagica, Globorotalia truncatulinoides, Globigerina inflata,* and *Globigerinella aequilateralis* are found, especially in the southern portion, but they appear to be "terminal immigrants" carried in by warm water from the regions to the south and west.

Although the transition fauna is best developed along the west coast of North America, there are also indications of its occurrence in other localities along the boundary of the cold and warm faunas. The species from Chinook stations 5 and 6 in the mid-Pacific and Transpac stations 52, 55, 56 and 60 northeast of Japan appear to belong to this group. The lack



TEXT FIGURE 36
Distribution of total planktonic Foraminifera from meter net samples



TEXT FIGURE 37
Distribution of total planktonic Foraminifera from Clarke-Bumpus and 17 cm. net tows

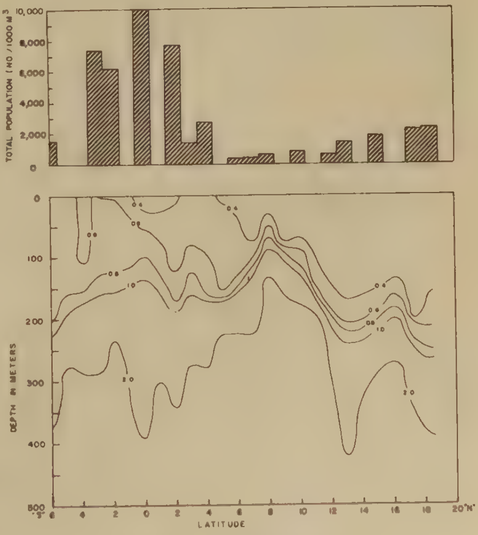
of closely spaced samples in these areas of rapid faunal change prevent more detailed delimitation of the areal extent of this fauna. There are indications of the presence of a transition fauna in the Peru Current, where the oceanographic conditions are similar to those of the California Current.

Warm-water faunas.—The area covered by these faunas includes the equatorial region and the central regions of the North and South Pacific. The northern boundary corresponds to the southern limit of the transition region as defined above. The 20° C isotherm associated with this boundary also presumably marks the southern extent of these faunas in the South Pacific.

Within this large region several minor faunal groups can be defined:

1. Central-water assemblage. This group is found in both the Western and Eastern Central Water masses of the North Pacific but appears to be absent, at least in surface layers, from the equatorial region. Representative species of this assemblage are: *Globigerina inflata, Globorotalia truncatulinoides.*

2. Equatorial west-central assemblage. This group consists of those species limited to water of the most tropical character, which in this area is defined by the Pacific Equatorial and Western North Pacific Central



TEXT FIGURE 38
Variations in abundance of total planktonic Foraminifera from one traverse across the equatorial region. Below are given phosphate concentrations (µg-atoms P/L) for the same section.

water masses. The following species are restricted to this area: *Globigerina conglomerata, Globigerinella* sp., *Globorotalia tumida, Pulleniatina obliquiloculata, Sphaeroidinella dehiscens.*

One of these species (*Globigerina conglomerata*) may be limited to the equatorial region since it has not yet been reported from the west-central Pacific.

Mixed warm-water fauna.—Many species are found throughout the entire warm-water region although they may occur in higher frequencies in either the equatorial or the central assemblage.

The following species are more common in the central fauna although they also occur in the equatorial west-central region: *Candeina nitida, Globorotalia scitula, Hastigerina pelagica.*

The following species are more common in the equatorial west-central region although they also occur in the central fauna: *Globigerina hexagona, Globigerinella aequilateralis, Globigerinita glutinata, Globigerinoides conglobata, G. rubra, G. sacculifera, G.* sp., *Globorotalia hirsuta, G. menardii, Hastigerinella rhumbleri.*

Geographic Variations in Abundance of Planktonic Foraminifera

Text figures 36 and 37 show areal distributions of total populations from coarse and fine mesh net samples. Text figure 38 shows changes in the total population on one traverse crossing the equatorial region. In general, the various oceanographic regions support different concentrations of Foraminifera. The boundaries of these areas are generally similar to those defined for the faunal groups. The subarctic region (north of 45° N Lat.) is characterized by large total populations although the number of species is small. The greatest concentrations at a single station (560 specimens per m^3) was found at Transpac station 24 in this region.

The transition region contains a greater number of species than the subarctic and has somewhat smaller populations. At several stations near the mixing of the Kuroshio and Oyashio relatively small populations were recorded.

Samples from the equatorial region have variable total populations. At localities in the Equatorial Current system and in certain localized areas, such as the Gulf of California, extremely high populations are recorded from the coarse net samples. Elsewhere the populations may be relatively low. The few fine-mesh net hauls in this region indicate that total populations are lower than those in the subarctic region.

The central-water region generally supports the lowest foraminiferal concentrations found throughout the entire area examined.

Vertical Distribution of Foraminifera

Introduction.—A knowledge of the vertical range of planktonic Foraminifera in the water column is necessary for a better understanding of their regional distribution and for a better analysis of their complex relationships to their environment. Furthermore, in using planktonic Foraminifera from the sediments to interpret climatic conditions it is necessary to know what water depths are being interpreted. Phleger (1945, 1951) has discussed these problems and suggested certain methods of attack, some of which were used in the present study.

Most of the previous samples of living planktonic Foraminifera were taken by shallow net tows and were not quantitative. Very little direct evidence was available to support the idea expressed by Murray (1897, p. 22) that the planktonic Foraminifera live only at the ocean surface. Murray's opinion was based on the distribution of empty tests on the sea bottom and only partly on an analysis of net samples. Carpenter (1875) and Brady (1884), on the other hand, believed that the smaller and younger forms were to be found at the surface and that the larger, older ones lived on the bottom. Little evidence was presented favoring either viewpoint and it was not until the work of Lohmann (1920) that more facts were made available. Lohmann, in analyzing water samples from the Atlantic, found more specimens of *Globigerina* in the upper 100 m of water than at greater depths. The following table is taken from Lohmann's data:

Depth	Number of individuals
0 m	100
50 m	67
100 m	60
200 m	7
400 m	3

Schott (1935) presented data based on Nansen closing-net samples taken by the Meteor Expedition in the equatorial Atlantic Ocean. These data have been analyzed by Phleger (1945) as follows:

Depth in meters	No. of tows	Mean no. of spec./tow
0-100	71	489
100-200	7	8
200-400	13	24
400-600	19	10
600-800	12	11
800-1000	19	28

In these earlier studies on vertical distribution no distinction was made between the living Foraminifera and their empty tests. Only the living organisms should be considered when determining the living environment since dead or dying specimens sinking to the bottom would be expected at every depth. Phleger (1945, 1951) used a modification of the biuret test for protein in differentiating the living from the empty tests in plankton tows from the North Atlantic and the Gulf of Mexico. Phleger's data indicate a higher concentration of living and dead specimens in the upper 100 meters, although at some of his stations a greater concentration of living Foraminifera was found deeper.

Variations of total population with depth.—In addition to the samples taken for determination of geographic distribution, 61 samples were taken for the purpose of determining the depth preferences of the planktonic Foraminifera.

Table 1 shows the vertical distribution of various species from tows made at one locality in the Pacific. The following general observations have been drawn from these data:

1. The samples taken directly from the sea surface contain fewer specimens, in most of the tows, than those taken slightly deeper.

2. The highest concentrations of Foraminifera occur between 6 to 30 m in most tows. In no tow does the greatest concentration occur below 100 m.

3. The depth of greatest decrease in number per cubic meter occurs between 50 and 100 m in most tows.

4. Relatively low concentrations of specimens were noted below 200 m.

Diurnal migration.—Diurnal vertical migrations by many planktonic animals are well-known. At night the highest concentrations of individuals are reported near the surface while in the daytime the greatest concentrations are in the deeper water (Sverdrup *et al.*, 1942). Owen (1868, pp. 148, 156) reports that the highest concentrations of planktonic Foraminifera are near the surface at night. Rhumbler (1911, chart A) compares night and day tows in the North Atlantic, showing that in general the day tows have much higher concentrations of Foraminifera. Allan Bé (personal communication) reports that in surface net tows off Bermuda, "Three night tows were 30-40% poorer

LOCATION	LAT. 33°02'N. LONG. 118°23'W.																														
STATION	A					B											C				D										
TYPE OF NET	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
DEPTH IN METERS	0	0	10	50	100	5	10	25	40	60	60	80	100	150	200	400	0-5	10	25	40	5	10	25	40	60	80	100	150	200	300	400
TOTAL SAMPLE POPULATION	39	122	222	132	74	103	130	96	139	204	158	218	104	59	38	49	102	179	106	90	41	166	67	162	181	145	50	56	57	29	116
POPULATION PER 1000 M^3	36,000	53,000	89,000	70,000	55,000	40,000	124,000	107,000	87,000	85,000	93,000	64,000	28,000	18,000	13,000	21,000	79,000	200,000	101,000	65,000	22,000	123,000	67,000	108,000	87,000	79,000	50,000	11,000	10,000	10,000	16,000
Candeina nitida																															
Globigerina bulloides	13	20	20	16	27	32	23	12	22	30	22	23	18	7	5	10	17	22	23	22	22	25	16	20	22	22	18	21	12	7	17
conglomerata																															
eggeri	36	29	47	54	54	34	37	46	49	39	54	51	55	79	60	48	37	50	49	51	27	48	45	45	42	43	32	46	44	62	57
hexagona																															
inflata				1						1				1		12			1												
pachyderma														2	3															4	2
quinqueloba																2															
sp																															
Globigerinella aequilateralis			1			1	1	2	1	1		2	4				1	1	4	1	2	2	2	2	1	2	8	2	3		2
sp.																													2		1
Globigerinita glutinata									3	3	3	6		1	5	2	3	3	3	7	10	3	6	3	10	10	10	5	7	4	
Globigerinoides conglobata																															
cf. minuta																															
rubra	20	20	18	6	5	9	14	20	16	14	11	5	2	2	8	4	20	12	9	4	20	11	13	15	10	6	10	11	12	3	6
sacculifera																															
sp.	5	3	2	3		3	1	3			1	1					1	1	1		12	1		1	2	1					
Globorotalia hirsuta																															
menardii										1		1			3			1							1		2		2		
scitula													3																		3
truncatulinoides													1																		
tumida																															
Hastigerina pelagica																4														3	2
Hastigerinella rhumbleri																															1
Orbulina universa		2	2	1	3	5	3	3	1	1	5	1	3	3	11	4	4	3	3		2	3	3	4	2	1	4	4			3
Pulleniatina obliquiloculata																															
Sphaeroidinella dehiscens																															
unidentified globigerinids	25	26	10	19	11	16	21	14	8	10	4	10	14	5	5	14	17	7	7	9	5	7	15	10	11	15	16	11	18	17	6
unidentified globorotaliids																															

TABLE 1
Occurrence of planktonic Foraminifera at different depths in per cent of total population.

than the seven day tows taken at the same place. A similar observation is true between 2 day tows and 1 night tow taken at the same location in the Caribbean."

A comparison has been made between the concentrations of total planktonic Foraminifera per cubic meter in surface hauls at day and night stations in the Pacific to discover whether a similar relationship holds true here. The data have been taken from King and Demond (1953) for POFI cruises 2, 5, and 8. Data for POFI cruise 16 were taken from Hilda and King (1955). The ratio of night/day hauls in all cases is less than 1, indicating that there was greater concentration at the surface during the day.

POFI cruise 16 obtained data on concentration of total planktonic Foraminifera at the surface, in intermediate depths, and in deep water. Analysis shows that surface Foraminifera during the day are generally more abundant than they are at night, but in the deep samples the night catches average more than the day samples. This suggests that Foraminifera ascend to the surface during the day and descend at night.

A possible mechanism for this may be found in the probable day and night differences in oxygen production by the symbiotic algae in the protoplasm. During the day the oxygen may be produced so rapidly that bubbles are formed, causing the Foraminifera to rise toward the surface. The utilization of oxygen for respiration during the night would cause an increase of specific gravity resulting in the sinking from the upper layers.

DISCUSSION

Ecologic Factors

Each species tends to extend its range whenever possible by continuous pressure against its boundaries. The boundaries to a large extent are determined by the limiting effects of various environmental factors of which a large number exist. Hutchins (1947) has shown the importance of temperature in the observed ranges of benthic species and similar reasoning may be extended also to planktonic organisms. Food, oxygen, salinity, pH, dissolved inorganic and organic substances, and biological interactions are but a few of the possible additional factors having a direct effect upon distribution. For each species there exist maximum and minimum environmental limits for survival and reproduction. When the range of tolerance for many factors is wide the species may live over an extensive geographic range; if the range is narrow the form usually is restricted to a smaller area.

The tolerance range for reproduction generally is more limited than that for the mere survival of the adult forms. The occurrence of adult specimens does not necessarily indicate that the organism can reproduce there since currents may carry individuals into regions where ecologic factors will not permit reproduction.

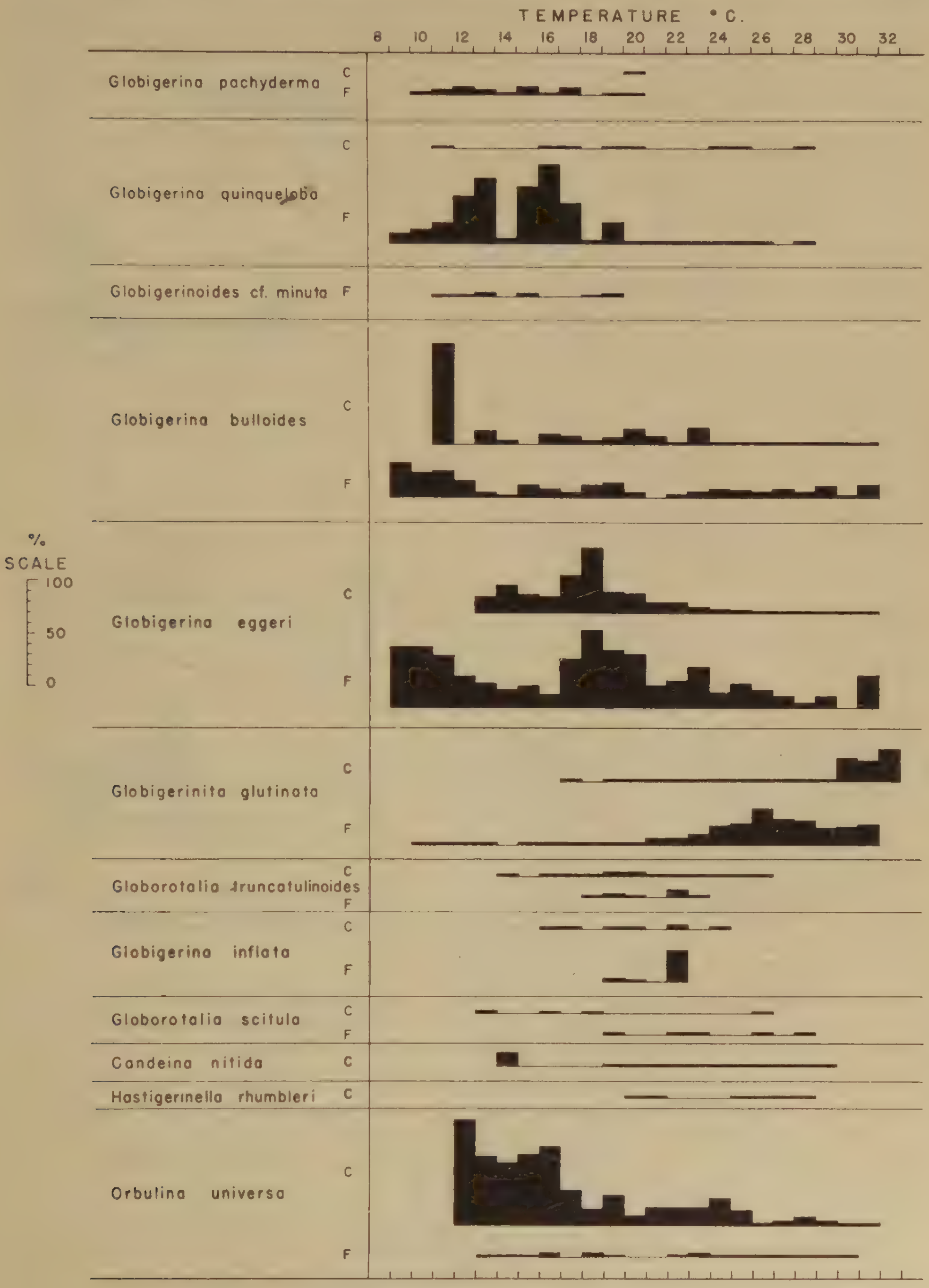
Only a few of the known environmental factors appear to be so variable that they affect the distribution of the planktonic Foraminifera in the region sampled. For example, oxygen concentrations are very close to saturation in the surface water, varying from approximately 4 to 6.5 ml per liter. The oxygen content may reach lower values at certain localities such as the Gulf of California where concentrations of 0.17 ml/L have been reported at 100 m. However, Sverdrup *et al.* (1942) state that even such low oxygen values as this are not known to be limiting to most planktonic organisms.

Temperature.—The distributions of most species show a general agreement with latitude, but an even better correlation with sea surface temperatures. For example, in the western Pacific off Japan the northern boundary of the "warm" fauna (typified by *Globorotalia menardii*) occurs at about 40° N Lat. but in the eastern Pacific the boundary is depressed farther south to approximately 20° N Lat. This boundary generally follows the 20° C surface isotherm.

The temperature ranges of the species, based on surface temperatures observed when the specimens were collected, are shown in Text figures 39 and 40. No one temperature can be shown to form a common boundary for any of the faunal groups but there are ranges of temperatures in which the greatest faunal changes are observed.

Text figure 41 shows the maximum number of species that have been found at each of the indicated temperatures during this study. It shows that as the temperature increases more species appear until an "optimum plateau" is reached. Fewer species are found at the highest temperatures. The region of greatest faunal change for all samples occurs between 12° and 18° C which corresponds to the temperature range at the Subarctic Convergence. The sharpness of the faunal boundary appears to depend upon the steepness of the horizontal temperature gradient. Marked temperature changes occur at the junction of the Kuroshio and Oyashio currents. Text figure 42 shows the dramatic change of fauna that occurs within a relatively short distance in this area. The broad transition zone, with no sharp faunal boundaries, along the west coast of North America can be correlated with the lack of a strong temperature gradient.

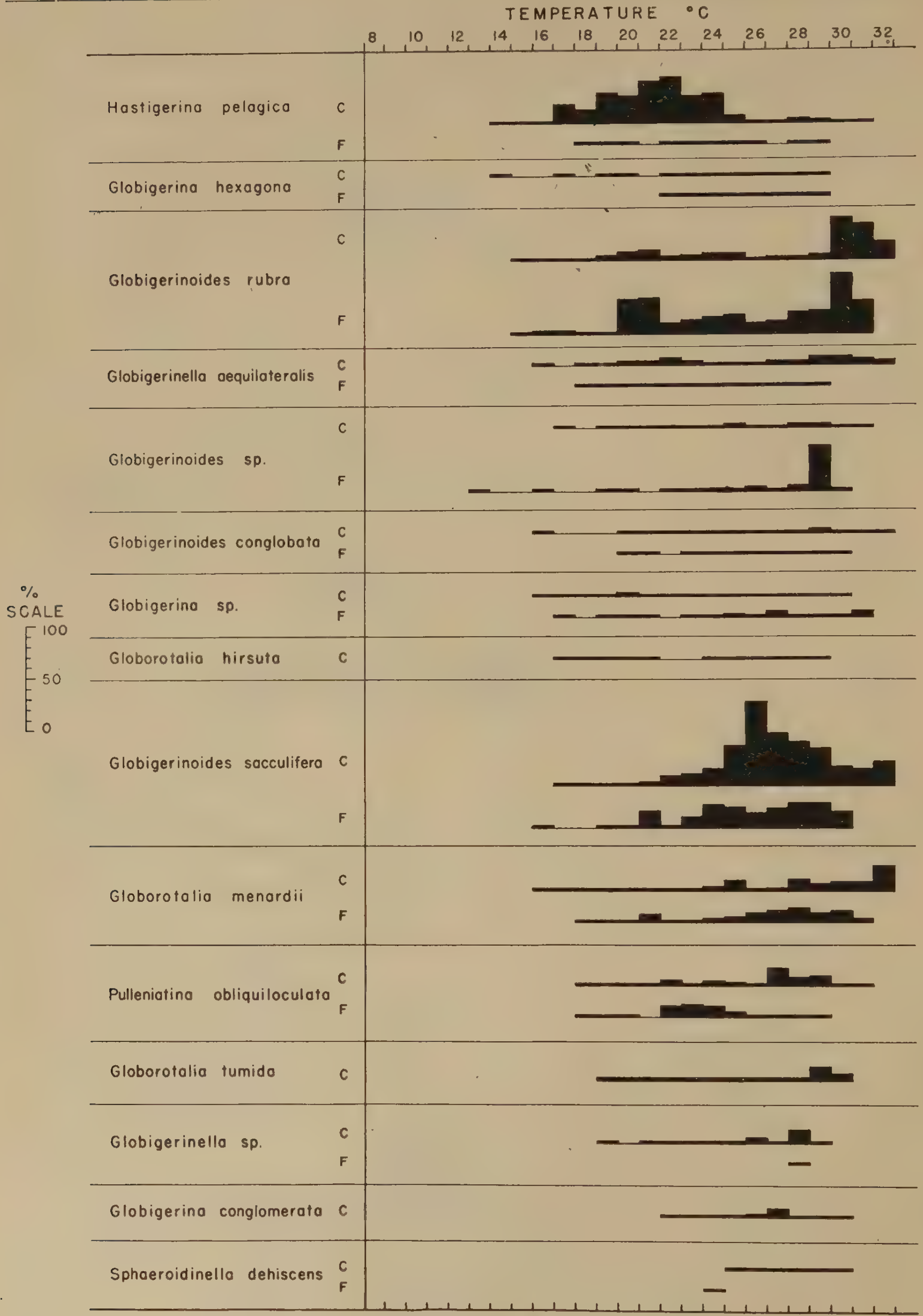
Water movement at the boundary of the warm and cold faunas confuses the picture to a certain extent. Text figure 42 shows that cold water from the Oyashio, which flows under the warm Kuroshio, is transporting cold water forms to the south. Warm water species carried to the north can survive only if they remain in the upper layer. Large-scale eddies are found where the mixing of the Kuroshio and Oyashio takes place. Eddies of water, each with its characteristic plankton community, may from time to time break off from the main water masses and carry the contained organisms a limited distance into unsuitable areas. Eventually the eddies or patches of warm or cold water will reach



TEXT FIGURE 39

Frequency of abundance of planktonic Foraminifera at different temperatures
"C" refers to coarse mesh samples (> 0.55 mm); "F" indicates fine mesh samples (> 0.14 mm).

(93)

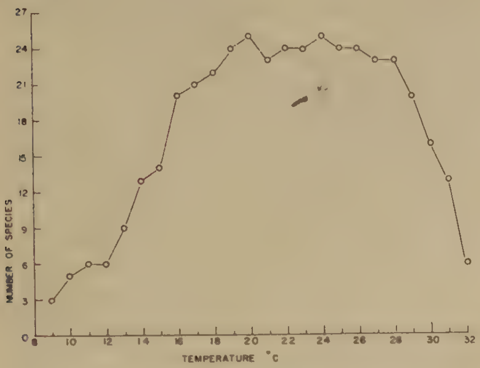


TEXT FIGURE 40

Frequency of abundance of planktonic Foraminifera at different temperatures
"C" refers to coarse mesh samples (> 0.55 mm); "F" indicates fine mesh samples (> 0.14 mm).

(94)

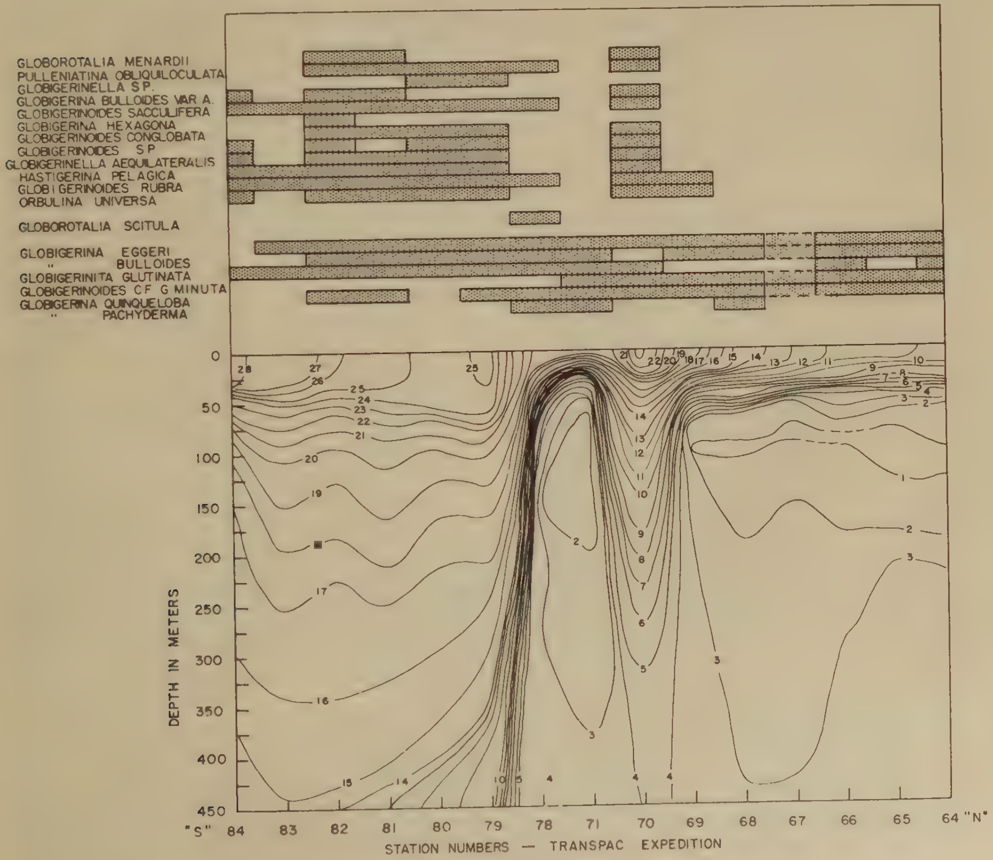
the temperature of the surrounding water and the contained organisms will be affected. When a warm-water form is carried into cold waters it may maintain itself for limited periods although it may not successfully reproduce. Bigelow (1926) and Redfield and Beale (1940) have shown that certain species of Chaetognatha and other organisms are not immediately killed when carried into colder water but, if conditions are not too extreme, will even grow to a larger size than they do in their normal warm-water habitat. In the Pacific a "sterile distribution" presumably occurs in the extensions of the Kuroshio into northern latitudes. This "cold tolerance" of planktonic forms and the problems in identifying very young stages make it difficult to define precisely the reproductive boundaries of each species.



TEXT FIGURE 41

Graph showing the maximum number of species found at the indicated temperatures.

The physiological effects of different temperatures upon living planktonic Foraminifera are not known since these forms have not been successfully cultured in the laboratory. It is possible that generalized information may be gained by controlled study of the effect of temperature upon benthonic species. Laboratory studies (Bradshaw, 1957) on *Streblus beccarii* (Linné) var. *tepida* (Cushman) indicate that a de-



TEXT FIGURE 42

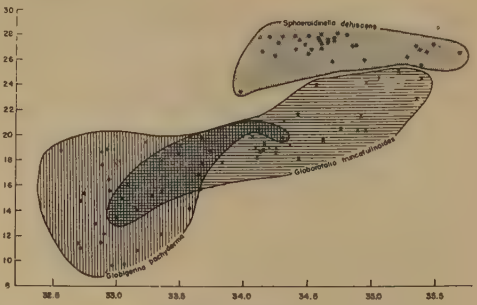
Vertical section across boundary of Kuroshio and Oyashio currents showing warm and cold faunal boundary crease in temperature results in a slower rate of growth, increased time to sexual maturity, and a larger size than was found in specimens kept at normal environmental temperatures. Lowering the temperature below 10° C appeared to halt the reproductive process indefinitely although the organisms remained alive and healthy.

Salinity.—Salinity usually is not considered as important an ecologic factor as temperature in the open sea. Very little is known of its effect upon oceanic plankton, however, and relatively slight changes of salt content may be important for such forms.

There appears to be a general relationship between the distribution of species of planktonic Foraminifera and surface salinities. There is the same southward depression of salinity values in the eastern Pacific as was noted in the temperature distribution. There is also a steep salinity gradient across the sharp faunal boundary off Japan while more gradual changes are found off the west coast of North America.

Ecologic water masses.—Variations of temperature and salinity are closely interrelated and until the effects of the two can be separated it may be best to consider them together. Simultaneous plots of temperature and salinity have been used by physical oceanographers as convenient descriptions of oceanographic water masses and as aids in differentiating one from another. Seasonal and local variations, however, limit the strict use of these defined water masses to depths deeper than 100 to 200 meters. The upper limit of the traditional water masses thus lies below the depth of maximum concentration of Foraminifera as indicated by this study. The need for a more comprehensive concept of the biological environment has led to the generalization of an ecologic water mass. This has been defined by Phleger (1954) as "any body of water which has a uniform ecologic effect and supports a uniform assemblage of organisms."

Although the temperature and salinity relationship of such a water mass is of obvious importance in limiting the distribution of species, more subtle, unknown biochemical factors undoubtedly play an important role.



TEXT FIGURE 43

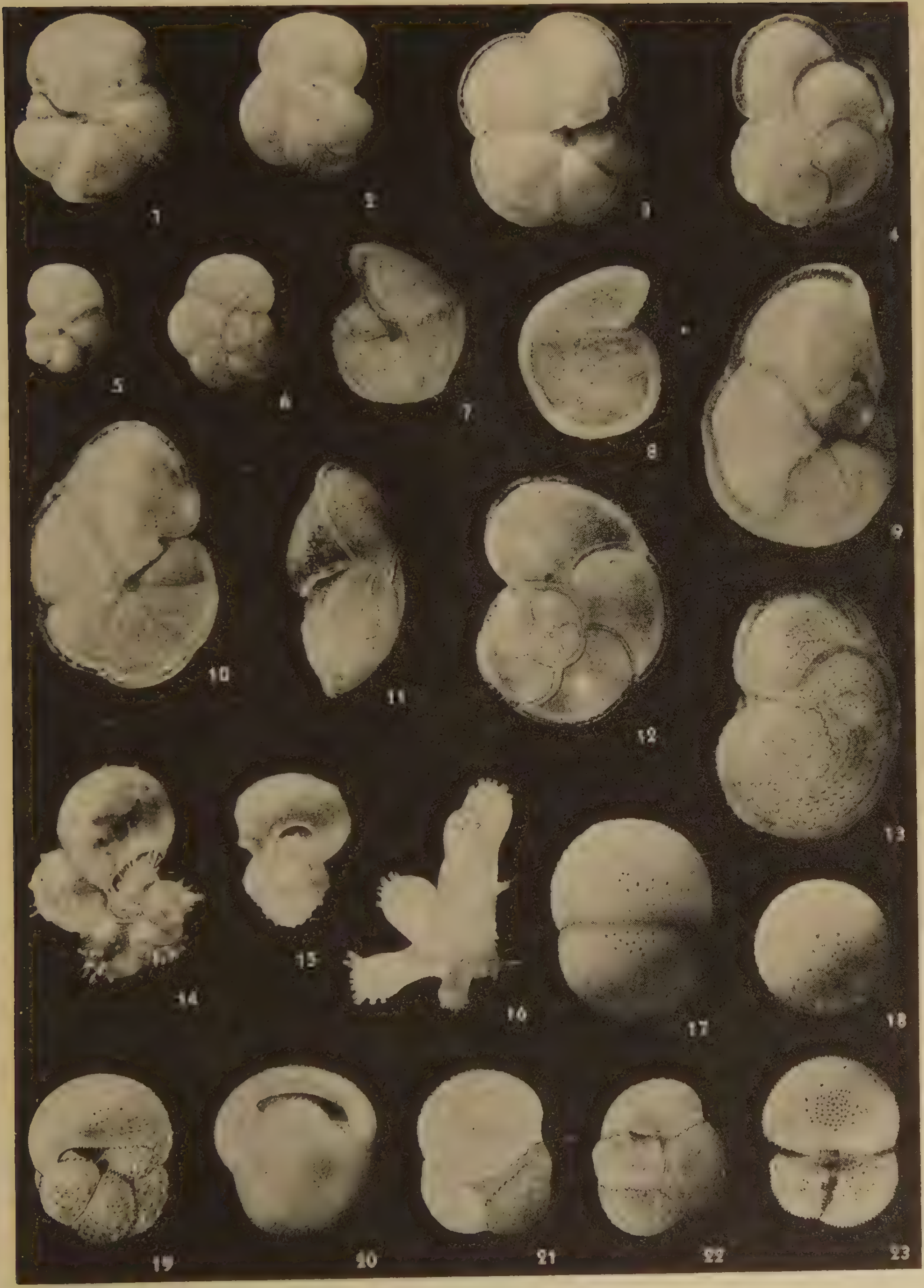
Temperature and salinity relations of water inhabited by three species of planktonic Foraminifera.

Bigelow (1926), Fraser (1954), Johnson (1939, 1949, 1954), Russell (1935), and Russell and Hastings (1933) have utilized planktonic organisms as indicators of water movements and to recognize bodies of water of varying but usually limited extent. Indicator organisms are often so sensitive to changes in physical-chemical properties that they have been used to identify water masses, where traditional oceanographic techniques fail. Bieri (1957), Brinton (1957) and Hida (1957) have used species of chaetognaths, euphausiids, and pteropods, respectively, to recognize large faunal regions in the Pacific that appear to be closely related to the surface oceanographic water masses.

The ranges in temperature and salinity values of the water inhabited by three species of Foraminifera, each illustrating one of the major faunal groups, are shown in Text figure 43. The values for the surface water are outside the limits of the defined water masses as shown in Text figure 5. Nevertheless, there still appears to be a natural division of the values into several clusters which in general represent the surface water overlying each of these water masses. One such grouping of high temperature and salinity, illustrated by *Sphaeroidinella dehiscens*, appears to be closely related to the Equatorial Pacific Water mass. A second group with lower temperatures and salinities, typified by *Globigerina pachyderma*, represents a surface mani-

EXPLANATION OF PLATE 8

FIGS.		PAGE
1, 2.	*Globorotalia hirsuta* (d'Orbigny). × 47. Shellback sta. 175	44
3, 4.	*Globorotalia menardii* (d'Orbigny). × 47. Shellback sta. 80	44
5, 6.	*Globorotalia scitula* (Brady). × 102. Shellback sta. 154	44
7, 8.	*Globorotalia truncatulinoides* (d'Orbigny). × 47. Transpac sta. 115	44
9, 13.	*Globorotalia tumida* (Brady). × 47. Norpac sta. 154.5	47
10-12.	*Globorotalia* cf. *G. menardii*. × 47. Variant form, Equapac-s sta. 36	44
14, 15.	*Hastigerina pelagica* (d'Orbigny). × 47. Shellback sta. 80	47
16.	*Hastigerinella rhumbleri* Galloway. × 47. Shellback sta. 80	47
17, 18.	*Orbulina universa* d'Orbigny. × 31. Troll sta. 14	49
19, 20.	*Pulleniatina obliquiloculata* (Parker and Jones). × 65. Equapac-s sta. 21	49
21-23.	*Sphaeroidinella dehiscens* (Parker and Jones). 21, 22, × 47; 23, variant form, × 31. Equapac-s sta. 21	49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Bradshaw: Living Planktonic Foraminifera, Pacific Ocean

festation of the Pacific Subarctic Water, while *Globorotalia truncatulinoides* illustrates a third grouping of intermediate values related to the Central Water masses. There is a certain amount of overlapping of these groups but it is believed that they reflect real differences in the character of the water.

Abundance of Planktonic Foraminifera

The Foraminifera form a significant fraction of the zooplankton. King and Demond (1953) show that Foraminifera average from 1.3 to 9.9 per cent of the total number of zooplankton organisms although they constitute a small fraction of the total mass of zooplankton. Marked seasonal changes in the relative abundance of Foraminifera are indicated by the change in average percentage composition from 1.8, 3.0, and 2.5 per cent in the three fall and winter cruises to 8.6 per cent in summer. In the winter cruises the most abundant zooplankton group was Copepoda, followed by Chaetognatha, Tunicata, Euphausiacea, Siphoniphora, and Foraminifera. In summer (cruise 5) Foraminifera increased in numerical importance becoming the third most numerous group, exceeded only by Copepoda and Chaetognatha. At two of their stations (7 and 9) Foraminifera made up 60 and 58 per cent of the total number of zooplankters, exceeding even the copepods. It should be remembered that these values are limited to the relatively large forms retained by the meter net. When finer mesh nets are used the relative numerical importance of the Foraminifera becomes even greater. Hida and King (1955) using Clarke-Bumpus samplers with nets of 0.31 mm aperture report that Foraminifera are the second most abundant zooplankton group during the summer in the equatorial Pacific.

Occurrence of Foraminifera in the plankton at any time reflects a complex interaction of physical-chemical and biological factors. The need for sufficient quantities of acceptable food is obvious. Since the food of planktonic Foraminifera consists of other plankters, their concentration is controlled in part by the same factors that control the bulk of the zooplankton.

The total zooplankton volumes (chart on file at Scripps Inst. Oceanography) and the concentration of total Foraminifera in the upper layers (Text figs. 36, 37) show the same pattern as the distribution of inorganic phosphate. The regions of abundant Foraminifera (equatorial, subarctic and along the American west coast) are also areas of high phosphate. These are in marked contrast to those in the centers of the great current gyrals which contain relatively low concentrations of Foraminifera and phosphate.

The large populations of Foraminifera near the equator probably are related to the greater overall fertility in this region than in the adjacent ones to the north and south. Vertical circulation and its effect on the abundance of total zooplankton in the equatorial region has been discussed by Cromwell (1953), King and Demond (1953) and King and Hida (1957). According to Cromwell (1953), the prevailing winds at the equator cause a divergence of the surface layers resulting in upwelling of nutrient-rich water. This fertilization is followed by extensive phytoplankton development and eventually by large zooplankton populations. A zone of convergence and associated sinking of the surface waters are expected to concentrate the zooplankton so that the highest numbers of individuals occur in the convergent zone. During south or southeast winds the convergence is believed to occur north of the equator, and south of the equator during a north or northeast wind. Since the prevailing winds in this region are east and southeasterly, the maximum concentration of zooplankton generally is expected north of the equator.

Variations with Depth

Tests of Foraminifera occur at all depths of water from the surface to the bottom. Ecological relationships of planktonic Foraminifera should be determined from specimens capable of carrying out their complete life cycle and not from specimens which are dead or incapable of reproduction. It is doubtful that species with highest concentrations in warm surface layers will be equally active in cold deep water. A species in this unfavorable position would soon die out were it not continuously restocked from the normal habitat above.

In the present study the largest specimens of many species were frequently found in the deepest samples. Similar observations have been reported by Murray (1895). The larger size may be due to continued growth of the organism if reproduction does not occur. Various examples of this in benthonic Foraminifera and other zooplankters have been mentioned previously.

Possible Faunal Changes with Depth

Closing-net tows were taken at various depths off San Diego, California, to determine if there were any restricted vertical distributions of species. The results are given in table 1. These data show no good evidence for restriction of the listed species to particular depths. Similar results were obtained by Phleger (1951) in the Gulf of Mexico and by Bé (personal communication) in the North Atlantic.

Some workers have postulated that various species are restricted to different depth levels. Emiliani (1954), using temperature data derived from the isotopic composition of Foraminifera tests, has calculated the depths at which various species live. This technique is based on the assumption that planktonic Foraminifera deposit calcium carbonate in equilibrium with the water. This is not necessarily true since exchange may occur between the oxygen liberated by the symbiotic organisms known to occur in many species of planktonic Foraminifera and the calcium carbonate which is being deposited. Problems of this type have been discussed by Emiliani (1955, p. 544) and by Epstein and Lowenstam (1953).

Emiliani (*op. cit.*, p. 545) notes that his isotopic temperatures represent the weighted average temperature of shell deposition of the foraminiferal population. Several hundred tests of each species were required to make up the 5 mg. of calcium carbonate required for each temperature determination and these tests were taken from core sections several centimeters in thickness representing long time-periods. It seems rather hazardous to use average isotopic temperatures over such a long time-period when the range of variations of these temperatures is unknown. It is well known, for example, that numerous fluctuations of climate have occurred in the last 1000 years. Taylor, Bigelow and Graham (1957) have shown that fluctuations of climate since 1900 are reflected in changes in distribution of certain marine species. Various warm- and cold-water species of planktonic Foraminifera also probably vary their geographic range in response to climatic trends. Certain cold-water species may be absent from an area during warm periods but be abundantly represented during cold periods.

Limited seasonal studies of planktonic Foraminifera (unpublished data) show that in areas of marked seasonal change different faunas may be present at different times of the year. Such seasonal changes in other planktonic organisms are well-known and usually have been related to changes in temperature of the water. Thus the empty tests of certain species found on the bottom may reflect the temperatures at certain periods only and not the mean temperatures as suggested by Emiliani (1955).

Bandy (1956, p. 187) suggested the minimum water depths at which certain species of planktonic Foraminifera live in the Gulf of Mexico. These depths are not based on the study of the Foraminifera in plankton samples but upon the depths at which their tests were found on the sea floor. The upper limits of the same species from plankton tows taken in the present study and by Phleger (1951, tables 2-9) do not agree with Bandy's findings. Many species reported by Bandy below his listed depths were found at or nearer the surface in the above plankton studies. Moreover, the order of occurrence of the tests of different species from shallow to greater depths in the Gulf of Mexico sediments corresponds approximately to the order of abundance of those species in the sediments, as listed by Parker (1954, p. 477). Thus, in shallow-water samples, which usually contain small numbers of planktonic specimens, the most common form would be more apt to appear than the rarer species. The probability of finding uncommon forms increases in deep water because of higher populations in the sediment.

There is some evidence, however, that cold-water species that live at the surface in the subarctic and temperate zones may live at lower temperatures below the warm surface water in the equatorial regions. This is true of many other planktonic organisms such as copepods, siphonophores, polychaetes, amphipods, chaetognaths, and radiolarians (Ekman, 1953, pp. 252 and 321). In view of this widespread occurrence in other invertebrate groups it would be surprising if planktonic Foraminifera did not exhibit this phenomenon, at least to a limited extent. "Tropical submergence" would be expected to influence primarily the cold-water group such as *Globigerina pachyderma, G. bulloides, G. quinqueloba,* and *Globigerinoides* cf. *G. minuta,* but also perhaps the temperate, stenothermal species such as *Globorotalia truncatulinoides* and *Globigerina inflata.* Eurythermal species, such as *Globigerina eggeri* and *Globigerinita glutinata,* can apparently tolerate warm temperatures and need not migrate into deeper waters to survive.

The lack of deep open-and-closing tows in the tropical Pacific prevents a thorough test of this hypothesis. However, occasional specimens of *Globigerina bulloides, G. quinqueloba, Globigerinoides* cf. *G. minuta* and *Globorotalia truncatulinoides* have been found in deep oblique tows from the equatorial and warm temperate regions. This suggests that they may occur at greater depths in that area. An alternative possibility is that they occur in the upper layers but at very low concentration. More extensive work on vertical distribution in the tropical regions is needed to decide this point.

Data from many deep open-and-closing hauls from 100 to 1000 m depth in the equatorial Atlantic were taken by Schott (1935, p. 62). *Globigerina bulloides* and *G. inflata* (both cold-temperate forms) were found in the deep tows but were not present in the surface waters (0 to 100 m) of the same region. Schott interpreted this as indicating submergence into colder waters for these normally cold-water species. His data suggest that *Globorotalia truncatulinoides* also may exhibit tropical submergence since it was found at 200 to 400 m depth and not in the upper layers of the equatorial Atlantic.

Although temperature appears to be the most critical factor in limiting the bathymetric distribution of various species, other factors, such as the effects of pressure, may be also of importance. The fact that the greatest populations are found in the upper zone of the sea, where the light is most intense, may be more than mere coincidence and may show sunlight to be of direct importance through its effect on the symbiotic algae known to be associated with the Foraminifera.

REFERENCES

Agassiz, Alexander, 1902, Report on the scientific results of the expedition to the tropical Pacific. I. Preliminary report and list of stations: Mus. Comp. Zool., Mem. 26 (1), pp. 1-114.

Bandy, O. L., 1956, Ecology of Foraminifera in northeastern Gulf of Mexico: U. S. Geol. Surv. Prof. Paper 274-G, pp. 179-204.

Bieri, Robert, 1957, Distribution of the planktonic Chaetognatha in the water masses of the Pacific. Unpublished PhD thesis, Univ. of Calif., Scripps Inst. Oceanography, La Jolla, Calif.

Bigelow, H. B., 1926, Plankton of the offshore waters of the Gulf of Maine: U. S. Bur. Fisheries, Bull. 40 (for 1924), pt. 2, 509 pp.

Bolli, H. M., Loeblich, A. R., Jr., and Tappan, Helen, 1957, Planktonic foraminiferal families Hantkeninidae, Orbulinidae, Globorotaliidae, and Globotruncanidae: *in* Studies in Foraminifera, U. S. Nat. Mus. Bull. 215, pp. 3-50.

Bradshaw, J. S., 1957, Laboratory studies on the rate of growth of the foraminifer, "*Streblus beccarii* (Linné) var. *tepida* (Cushman)": Jour. Paleontology, vol. 31, no. 6, pp. 1138-1147.

Brady, H. B., 1884, Report on the Foraminifera dredged by H. M. S. "Challenger" during the years 1873-1876: Rept. Voy. *Challenger*, Zoology, vol. 9, 1 vol. text, 814 pp.; 1 vol. pls. 1-115.

Brinton, Edward, 1957, Distribution, faunistics and evolution of Pacific euphausiids: Unpublished PhD thesis, Univ. of Calif., Scripps Inst. Oceanography, La Jolla, Calif.

Carpenter, W. B., 1875, Remarks on Prof. Wyville Thomson's preliminary notes on the nature of the sea-bottom procured by the soundings of H. M. S. "Challenger": Proc. Royal Soc. 23, pp. 234-245.

Carsola, A. J., 1952, Marine geology of the Arctic Ocean and adjacent seas off Alaska and northwestern Canada: Unpublished PhD thesis, Univ. of Calif., Scripps Inst. Oceanography, La Jolla, Calif.

Clarke, G. L., and Bumpus, D. F., 1940, The plankton sampler, an instrument for quantitative plankton investigations: Amer. Soc. Limnology and Oceanography, Spec. Publ. 5, pp. 1-8.

Cromwell, Townsend, 1953, Circulation in a meridional plane in the central equatorial Pacific: Jour. Mar. Res., vol. 12, no. 2, pp. 196-213.

———, 1954, Mid-Pacific oceanography. II. Transequatorial waters, June-August 1950, January-March 1951: U. S. Fish and Wildlife Serv., Spec. Sci. Rept. no. 131, 180 pp.

Cushman, J. A., 1914. A monograph of the Foraminifera of the North Pacific Ocean. Pt. IV. Chilostomellidae, Globigerinidae, Nummulitidae: U. S. Nat. Mus. Bull. 71, pt. 4, pp. 1-46.

———, 1921, Contributions to the biology of the Philippine Archipelago and adjacent seas: U. S. Nat. Mus., Bul. 100, pp. 1-608.

———, 1927, Recent Foraminifera from off the west coast of America: Bull. Scripps Inst. Oceanography, Tech. Ser., vol. 1, no. 10, pp. 119-188.

———, Todd, Ruth and Post, R. J., 1954, Recent Foraminifera of the Marshall Islands: U. S. Geol. Survey Prof. Paper 260-H, pp. 319-384.

Ekman, Sven, 1953, Zoogeography of the Sea: Sidgwick and Jackson Ltd., London, 417 pp.

Emiliani, Cesare, 1954, Depth habitats of some species of pelagic Foraminifera as indicated by oxygen isotope ratios: Amer. Jour. Sci., vol. 252, pp. 149-158.

———, 1955, Pleistocene temperatures: Jour. Geology, vol. 63, no. 6, pp. 538-578.

Epstein, S. and Lowenstam, H. A., 1953, Temperature-shell-growth relations of Recent and interglacial Pleistocene shoal water biota from Bermuda: Jour. Geology, vol. 61, pp. 424-438.

Fraser, J. H., 1954, Warm water species in the plankton off the English Channel entrance: Jour. Mar. Biol. Assoc. U. K., vol. 33, pp. 345-346.

Graham, H. W. and Moberg, E. G., 1944, Scientific results of Cruise VII of the CARNEGIE during 1928-1929, Chemistry I. Chemical results of the last cruise of the CARNEGIE: Publ. Carnegie Inst. Washington, no. 562, pp. 1-58.

Hentschel, E., 1934, Allgemeine Biologie des Südatlantischen Ozeans. Ergeb. deutsch. Atlantische Exped. METEOR 1925-1927, Bd. XI, pp. 3-344.

Heron-Allen, E. and Earland, A., 1922, Foraminifera: British Antarctic ("Terra Nova") Exped., vol. 6, no. 2, pp. 25-268.

Hida, T. S., 1957, Chaetognaths and pteropods as biological indicators in the North Pacific: U. S. Fish and Wildlife Service, Spec. Sci. Rept. no. 215, 13 pp.

———, and King, J. E., 1955, Vertical distribution of zooplankton in the central equatorial Pacific, July to August 1952:. U. S. Fish and Wildlife Service, Spec. Sci. Rept. 144, pp. 1-22.

Hutchins, L. W., 1947, The bases for temperature zonation in geographic distribution: Ecol. Monogr,, vol. 17, pp. 325-335.

Hofker, J., 1959, On the splitting of *Globigerina:* Contr. Cushman Found. Foram. Research, vol. 10, pt. 1, pp. 1-9.

Johnson, M. W., 1939, The correlation of water movements and dispersal of pelagic larval stages of certain littoral animals, especially the sand crab, *Emerita:* Jour. Mar. Research, vol. 2, no. 3, pp. 236-245.

———, 1949, Zooplankton as an index of water exchange between Bikini Lagoon and the open sea: Am. Geophysics Union Trans., vol. 30, pp. 238-244.

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———, 1954, Plankton of the northern Marshall Islands: U. S. Geol. Survey Prof. Paper 260-F, pt. 2, Oceanography (Biologic), pp. 301-314.

King, J. E. and Demond, J., 1953, Zooplankton abundance in the central Pacific: U. S. Fish and Wildlife Service, Fish. Bull. 82, pp. 111-144.

———, and Hida, T. S., 1957, Zooplankton abundance in the central Pacific, Part 2: U. S. Fish and Wildlife Service Fish. Bull. 118, pp. 365-395.

Lohmann, Hans, 1920, Die Bevölkerung des Ozeans mit Plankton nach den Ergebnissen der Zentrifugenfänge wahrend der Ausreise der "Deutschland" 1911: Arch. Biontologie, vol. 4, no. 3, pp. 1-617.

Murray, John, 1895, Summary of the scientific results obtained at the sounding, dredging and trawling stations of H. M. S. CHALLENGER: Challenger Repts., Summary, pts. 1 and 2, pp. 1-1608.

———, 1897, On the distribution of the pelagic Foraminifera at the surface and on the floor of the ocean: Nat. Sci., vol. 11, pp. 17-27.

Natland, M. L., 1938, New species of Foraminifera from off the west coast of North America and from the later Tertiary of the Los Angeles Basin: Bull. Scripps Inst. Oceanography, Tech. Ser., vol. 4, pp. 137-164.

Owen, S. R. J., 1868, On the surface-fauna of mid-ocean: Jour. Linn. Soc. London (Zoology), vol. 9, pp. 147-157.

Parker, F. L., 1954, Distribution of the Foraminifera in the northeastern Gulf of Mexico: Bull. Mus. Comp. Zool., vol. 106, pp. 391-423.

———, 1958, Eastern Mediterranean Foraminifera: Repts. Swedish Deep-Sea Exped. 1947-48, vol. 8, fasc. 2, No. 4, pp. 219-283.

Phleger, F. B, 1945, Vertical distribution of pelagic Foraminifera: Am. Jour. Sci., vol. 243, pp. 377-83.

———, 1951, Ecology of Foraminifera, northwest Gulf of Mexico. Pt. 1, Foraminifera distribution: Geol. Soc. America, Mem. 46, pp. 1-88.

———, 1952, Foraminifera distribution in some sediment samples from the Canadian and Greenland Arctic: Contr. Cushman Found. Foram. Research, vol. 3, pp. 80-89.

———, 1954, Foraminifera and deep-sea research: Deep-sea Research, vol. 2, pp. 1-23.

———, Parker, F. L., and Peirson, J. F., 1953, North Atlantic Foraminifera: Repts. Swedish Deep-Sea Exped., vol. 7, fasc. 1, pp. 3-122.

Redfield, A. C. and Beale, A., 1940, Factors determining the distribution of populations of Chaetognatha in the Gulf of Maine: Biol. Bull., vol. 79, pp. 459-487.

Rhumbler, Ludwig, 1911, Die Foraminiferen (Thalomophoren) der Plankton-Expedition, etc., Pt. 1. Systematik: Ergeb. Plankton-Exped. Humboldt Stift., Bd. 3, 331 pp.

Russell, F. S., 1935, On the value of certain plankton animals as indicators of water movements in the English Channel and North Sea: Jour. Mar. Biol. Assoc. U. K., vol. 20, no. 2, pp. 309-332.

———, and Hastings, A. B., 1933, On the occurrence of pelagic tunicates (Thaliacea) in the waters of the English Channel off Plymouth: Jour. Mar. Biol. Assoc. U. K., vol. 18, no. 2, pp. 635-640.

Schott, W., 1935, Die Foraminiferen in dem äquatorialen Teil des Atlantischen Ozeans: Wiss. Ergeb. deutsch. Atlantische Exped. METEOR 1925-1927, Bd. 3, pt. 3, Sect. B, pp. 43-134.

Sverdrup, H. U., and Fleming, R. H., 1941, The waters off the coast of southern California, March to July 1937: Bull. Scripps Inst. Oceanography, vol. 4, no. 10, pp. 261-378.

———, Johnson, M. W., and Fleming, R. H., 1942, The Oceans, their physics, chemistry and general biology: Prentice Hall, N. Y., 1087 pp.

Taylor, C. C., Bigelow, H. B., and Graham, H. W., 1957, Climatic trends and the distribution of marine animals in New England: U. S. Fish and Wildlife Service, Fish. Bull. 115, vol. 57, pp. 293-345.

Walton, W. R., 1952, Techniques for the recognition of living Foraminifera: Contr. Cushman Found. Foram. Research, vol. 3, pp. 56-60.

Wiseman, J. D. H., and Ovey, C. D., 1950, Recent investigations on the deep-sea floor: Proc. Geol. Ass., vol. 61, pt. 1, pp. 28-84.

Wooster, W. S., 1953, Phosphate in the eastern North Pacific Ocean: Unpublished PhD thesis, Univ. of Calif., Scripps Inst. Oceanography, La Jolla, Calif.

———, and Cromwell, Townsend, 1958. An oceanographic description of the eastern tropical Pacific: Bull. Scripps Inst. Oceanography, vol. 7, no. 3, pp. 169-282.

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SILICEOUS ORGANIC REMAINS IN PELAGIC SEDIMENTS

BY

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SILICEOUS ORGANIC REMAINS IN PELAGIC SEDIMENTS

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ABSTRACT

Siliceous skeletal remains, principally of diatoms and radiolarians with smaller amounts of sponge spicules and silicoflagellates, constitute up to approximately 40 percent of some Recent pelagic sediments. The main factors controlling the contribution made by siliceous organisms to marine sediments are apparently (1) the rate of production of siliceous organisms in the overlying waters, (2) the degree of dilution of siliceous remains by terrigenous, volcanic and calcareous organic contributions to the sediment and (3) the extent of solution of the siliceous skeletons, most of which apparently occurs shortly after deposition. Depth of water is apparently not an important direct factor, except insofar as it affects the amount of calcareous contributions to the sediments. The evidence at present available indicates that the production of siliceous organisms is high in the regions of the equatorial current systems and around the edges of the central water masses of the oceans, especially in areas of upwelling, and is much lower in those parts of the oceans in which the near-surface waters are more stably stratified.

INTRODUCTION

Ever since Ehrenberg (1844, 1856) described marine sediments consisting in large part of microscopic, siliceous skeletal remains of organisms, geologists have been interested in their distribution and the conditions necessary for their formation. By definition, such sediments can be formed only in those localities at which the supple of siliceous skeletons reaching the sea floor is high as compared with the supply of other sedimentary constituents such as calcareous skeletons and terrigenous debris. Terrigenous mineral grains of sizes larger than silt are not usually transported in large quantity more than a few hundred miles from the land, and therefore the open sea environment is that in which are found most of the large areas of sediments containing a high proportion of siliceous organic remains, though under certain conditions thick sequences of highly diatomaceous sediments may be deposited quite close to land or in enclosed arms of the sea.

The term "pelagic"—originally meaning 'of, or pertaining to, the open sea'—is difficult to define precisely in its application to sediments, but it is now in such common use that a clear definition is needed. As pointed out by Revelle *et al.* (1955), the sediments of the open sea in general are characterized by their being "derived in major part from particles (organic or inorganic) which settled out or were precipitated from the overlying water column, . . . without much terrigenous material above clay size." It does not seem convenient at present to include in the definition of the term "pelagic" that such sediments must be deposited "far from continents." Under certain special conditions, sediments consisting largely of the skeletal remains of planktonic organisms, and containing little coarse terrigenous debris, can be deposited close to continental land. Such sediments may be included within the term "pelagic" because their characters are not to any large extent dependent upon their proximity to land. It may be desirable later to define a special term to include these sediments which are not truly pelagic in the sense of being deposited in the open sea. Examples of pelagic sediments now being deposited in enclosed arms of the sea are the diatomaceous muds of parts of the Gulf of

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California (Revelle, 1950) and of the Sea of Okhotsk (Bezrukov, 1955).

An incidental characteristic of pelagic sediments is that their nature is only to a relatively small degree influenced by the action of waves and strong currents. Recent evidence from bottom photographs (Dietz, 1955, fig. 3) and stratigraphic considerations (Revelle *et al.*, 1955; Riedel, 1957) indicates that pelagic sediments are disturbed to some extent by currents even at great depths in the open ocean, but the action of waves and currents is much more intense in shallower environments.

It is obvious that between the littoral zone, where the character of the sediment is predominantly dependent upon the supply of terrigenous debris and upon the action of waves and currents, and the abyssal regions most remote from continents, there must be in general a gradation in the degree to which the nature of the sediment is dependent upon the influence of continental land. Therefore the pelagic environment is divided into "eupelagic" (truly pelagic) and "hemipelagic" (half or semi-pelagic), acording to the extent of the influence of the land, usually measured in terms of the amount of contribution of coarse terrigenous debris.

Of marine sediments now forming part of continents or islands, only a few types such as the exceptionally pure diatomaceous earths of the Californian Monterey Formation and the chalks of the European Cretaceous and the Selma Formation of Mississippi could be described as "eupelagic" in the sense defined above. And it seems likely that practically all of these fossil "eupelagic" sediments were deposited on continental shelves or borderlands, many of them in enclosed arms of the sea, and thus not in truly open-sea environments.

The distribution of siliceous organic remains in the pelagic sediments of part of the Pacific basin, and the factors determining this distribution, will be considered after a brief description of the organisms forming them.

For stimulating discussions of various aspects of this study, the author is grateful to M. N. Bramlette, R. W. Holmes, T. Cromwell and E. H. Ahlstrom. This paper is based in part on results of research carried out under contract with the U. S. Office of Naval Research.

TYPES OF SILICEOUS ORGANIC REMAINS

The four types of organisms which contribute significant quantities of siliceous skeletal remains to pelagic sediments are, in order of decreasing importance, diatoms, radiolarians, sponges and silicoflagellates.

Diatoms.—These minute plants which supply siliceous frustules to pelagic sediments are restricted to the upper 100-200 meters of ocean waters: the amount of light penetrating to greater depths is insufficient for their photosynthetic processes. Diatoms occur in the plankton of all parts of the oceans, and are particularly abundant at high latitudes, in some coastal waters, and in regions of upwelling where deeper water with fresh supplies of nutrients is brought up into the photic zone. The diatom frustules most commonly found in pelagic sediments have the form of thin, punctate, circular or elongate plates, with their greatest dimensions of the order of 20-200 μ.

As compared to the large contribution made to pelagic sediments by marine planktonic diatoms, a relatively small number of frustules of benthonic and fresh-water species are transported by winds and currents to areas of hemipelagic and eupelagic sedimentation. In some pelagic sediments far removed from land, fresh-water diatoms are accompanied by rare silicified epidermal cells of grasses (Kolbe, 1955, 1957).

Radiolaria.—Two large groups of the Radiolaria, the Acantharia and Tripylea, are absent or very rare in pelagic sediments; members of the former group have skeletons of strontium sulphate, and in the latter group the skeletons are apparently of a mixture of opaline silica and organic matter. For the purposes of this paper, therefore, the term 'Radiolaria' is used as embracing only the Spumellaria and Nassellaria, which are the only groups represented in considerable numbers in pelagic sediments. Spumellaria and Nassellaria occur in the upper waters of all the oceans; most of the species are found living only at depths of 0-400 meters. They are planktonic protozoans with opaline siliceous skeletons usually having dimensions of the order of 50-250 μ. The skeletons exhibit a great variety of form, some of the more common basic forms being series of concentric spiny spheres or ellipsoids, spongy discs with radiating spines or three or four spongy arms, and conical structures divided transversely into a number of segments. Most radiolarian skeletons are formed of a siliceous meshwork which is much more robust than the thin, perforated diatom frustules. Radiolaria occur in greater numbers in warmer than in colder waters, and in this respect their distribution tends to complement that of the diatoms.

Sponges.—Some of the members of this group of sedentary, multicellular animals secrete robust, opaline siliceous spicules. As some sponges are able to live even in abyssal oceanic depths, their spicules are contributed to pelagic sediments although the organisms are not planktonic. The spicules are usually of the order of one or a few millimeters in length, and are acicular, or irregular, or radiating in form. Sponge spicules are found in small numbers in practically all pelagic sediments, but they constitute only a very small part of the total biogenous silica except in some areas of relatively shallow water, and in some deep-sea clays from which the more delicate diatom and radiolarian skeletons have been dissolved.

Silicoflagellates.—These planktonic microscopic flagellates are by many authors considered to be algae, though the extent to which their nutrition is holophytic remains questionable. They occur in all oceans, and it seems probable that they may inhabit only the upper few hundred meters of water. They are apparently more numerous in colder than in warmer waters, though they are widespread in all latitudes. Enclosed in the protoplasmic body is an opaline siliceous skeleton consisting essentially of a hollow-spiny ring, the interior of which is in most species subdivided by a few meshes. The dimensions of the skeletons generally range between 20 and 100 μ. Silicoflagellates are widespread in pelagic sediments, but their percentage contribution to the total biogenous silica is at least one order of magnitude less than that of the other siliceous skeletons in all samples examined for the present study.

BIOGENOUS SILICA IN SOME PACIFIC SEDIMENTS

While the weight-percentage of biogenous calcium carbonate in pelagic sediments can be determined rather easily and accurately by chemical methods (because practically all of the calcium carbonate in pelagic sediments is biogenous), the quantitative determination of biogenous silica in sediments is difficult and rarely attempted. This is due to the difficulty of distinguishing chemically between the fine particles of biogenous opaline silica and inorganic quartz, both of which are present in pelagic sediments.

In order to obtain a body of data for discussion, the author has estimated visually the weight-percentages of biogenous silica in the carbonate-free fractions of some 85 sediment samples from a portion of the Pacific Ocean bounded by the longitudes 180° and 110°W and the latitudes 20°S and 60°N. The majority of the samples are from sediment cores, and are taken as nearly as possible from the tops of the cores. Care was taken to exclude, as far as possible, samples from submarine outcrops of pre-Quaternary sediments, or from areas in which reworked siliceous skeletons from Tertiary sediments form a large part of the total biogenous silica. By estimating the biogenous silica in the carbonate-free fractions of the samples, one eliminates one of the most important variables influencing the proportion of biogenous silica in the total sediment. The chart showing the distribution of sediment types (fig. 1) indicates the areas in which biogenous calcium carbonate is a major constituent of the sediments.

The visual estimation of the biogenous silica in the samples was made microscopically after treating small quantities of sediment with hydrochloric acid on microscope slides. Water was used as a mounting medium, in order that clay particles and siliceous organic remains might be seen with approximately equal clarity. When sediments are mounted in Canada balsam, which has a refractive index close to that of clay particles and considerably higher than that of opal, it is easy to overestimate the proportion of biogenous silica to inorganic constituents. It must be emphasized that the estimated values for biogenous silica are possibly very inaccurate. They have been made, however, by one observer over a short period of time, and therefore offer a better basis for comparisons than would scattered observations by different workers using a variety of techniques.

The samples used in this study are listed in table 1, and the estimated weight-percentages of biogenous silica

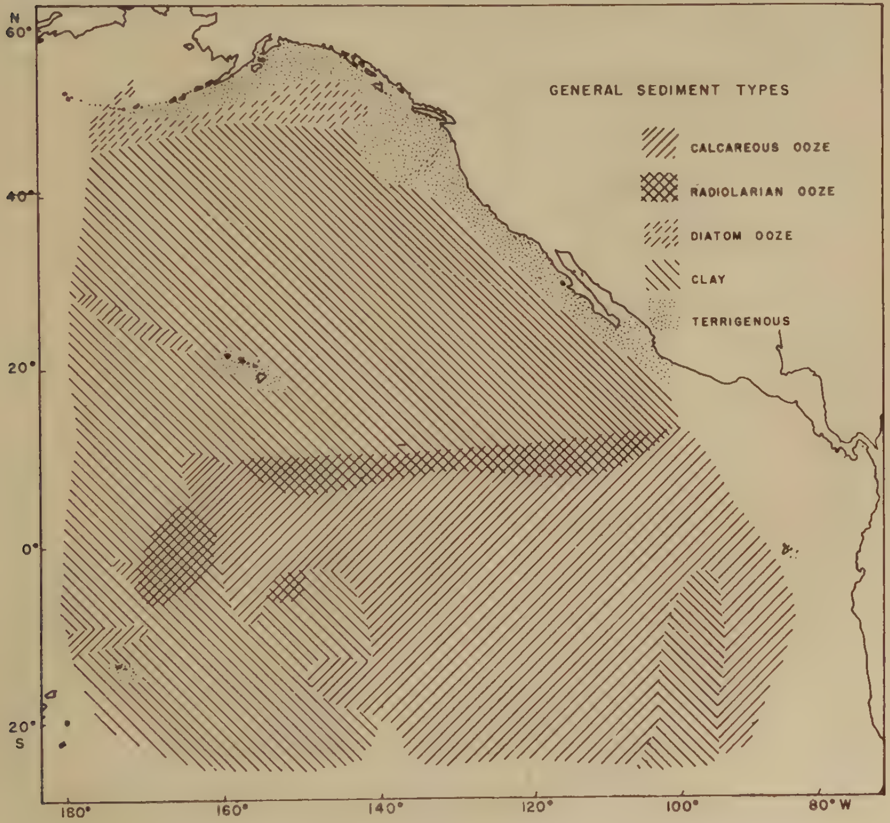


FIG. 1. Generalized distribution of sediment types in part of the Pacific Ocean. (After Revelle *et al*, 1955.)

in the carbonate-free portions of the sediments are plotted on a chart in fig. 2. The collectors of the sediment samples are abbreviated as follows:

Cap.; Capricorn Expedition of Scripps Institution of Oceanography, 1952-53.

Ch.; Chubasco (or Acapulco Trench) Expedition of Scripps Institution of Oceanography, 1954.

Ck.; Chinook Expedition of Scripps Institution of Oceanography, 1956.

Cusp; Cusp Expedition of Scripps Institution of Oceanography, 1954.

Gui. 23; U. S. Coast and Geodetic Survey Ship 'Guide,' cruise of 1923.

MP; MidPac Expedition of Scripps Institution of Oceanography and U. S. Navy Electronics Laboratory, 1950.

NEL-H; U. S. Navy Electronics Laboratory Expedition to Hawaii, 1953.

Nth. Hol.; Northern Holiday Expedition of Scripps Institution of Oceanography, 1951.

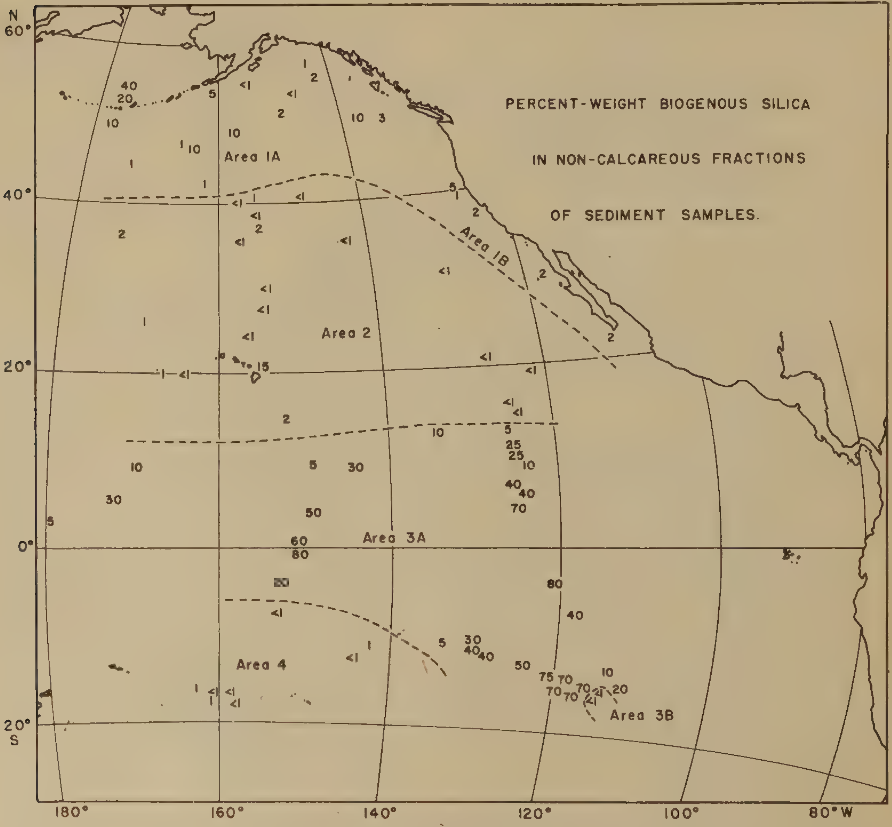
Pion. 22 and Pion. 29; U. S. Coast and Geodetic Survey Ship 'Pioneer', cruises of 1922 and 1929, respectively.

Swed.; Swedish Deep-Sea Expedition aboard the 'Albatross,' 1947-48.

U.W.; University of Washington cruises nos. 110 (in 1955) and 144 (in 1956) aboard the 'Brown Bear.'

THE DISTRIBUTION PATTERN

For the purpose of this discussion, the part of the Pacific from which the sam-


PERCENT-WEIGHT BIOGENOUS SILICA
IN NON-CALCAREOUS FRACTIONS
OF SEDIMENT SAMPLES.
N 60°
40°
20°
0°
20° S
180°
160°
140°
120°
100°
80° W
Area 1A
Area 1B
Area 2
Area 3A
Area 3B
Area 4
40
20
10
5
<1
2
10 3
10
10
1
1
<1
5
2
<1
2
<1
<1
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1
<1
Area 2
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2
10
10
5 30
5
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25
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40
40
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80
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<1
1
5
30
40
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75 70
10
70 70 70 <1 20
1
<1
<1
<1

FIG. 2. Estimated weight-percentages of biogenous silica in the non-calcareous fractions of sediments at various localities in the Pacific Ocean. Areas 1A-4 are discussed in the text.

TABLE 1

Collector	Core or Sample No.	Depth below sediment surface (cm.)	Latitude	Longitude	Depth (m.)	Sediment type	Percent-wt. biogenous silica in carbonate-free fraction
Cap.	30 BG	0–4	17°28'S	160°59'W	4710	Zeolitic clay	<1
Cap.	31 BG	0–4	17°29'S	158°40'W	4890	Zeolitic clay	<1
Cap.	33 BG	0–4	12°46'S	143°33'W	4380	Zeolitic calcareous clay	<1
Cap.	34 BG	0–4	11°20'S	142°26'W	4500	Zeolitic calcareous clay	1
Cap.	36 BG I	0–4	10°45'S	133°35'W	4490	Calcareous clay	5
Cap.	37 BG II	0–4	11°46'S	128°55'W	3900	Calcareous ooze	40
Cap.	38 BG I	0–4	14°16'S	119°11'W	3400	Calcareous ooze	70
Cap.	39 BG II	0–4	15°02'S	113°49'W	3400	Calcareous ooze	<1
Cap.	40 BG I	0–4	14°47'S	112°08'W	3020	Calcareous ooze	20
Cap.	41 BG I	1–4	13°33'S	113°21'W	2940	Calcareous ooze	10
Cap.	42 BG I	0–4	7°19'S	118°40'W	4230	Calcareous ooze	40
Cap.	44 BG	0–4	3°42'S	121°03'W	4170	Calcareous ooze	80
Cap.	48 BG II	0–1	5°49'N	124°03'W	4125	Calc.-siliceous clay	40
Cap.	49 BG	0–4	9°17'N	124°09'W	4410	Radiolarian clay	10
Cap.	50 BG II	0–4	14°55'N	124°12'W	4270	'Red' clay	<1
Cap.	21 HG	1–4	16°36'S	162°43'W	5125	Zeolitic clay	<1
Cap.	23 HG	1–4	16°59'S	161°35'W	5140	'Red' clay	<1
Cap.	24 HG	1–4	16°44'S	161°22'W	4685	'Red' clay	<1
Cap.	25 HG	1–4	16°53'S	159°08'W	5040	Zeolitic clay	<1
Cap.	33 HG	0–1	10°58'S	130°30'W	4040	Calcareous ooze	30
Cap.	35 HG	1–4	10°59'S	130°13'W	4025	Calcareous ooze	40
Cap.	36 HG	1–4	11°00'S	130°06'W	4320	Calcareous ooze	40
Cap.	37 HG	0–1	13°05'S	124°17'W	3850	Calcareous ooze	50
Cap.	38 HG	0–1	14°17'S	120°41'W	3590	Calcareous ooze	75
Cap.	39 HG	0–1	14°43'S	120°01'W	3360	Calcareous ooze	70
Cap.	40 HG	1–4	15°13'S	117°30'W	3550	Calcareous ooze	70
Cap.	41 HG	0–1	15°56'S	117°14'W	3394	Calcareous ooze	70
Cap.	42 HG	0–1	15°39'S	114°18'W	3221	Calcareous ooze	<1
Ch.	1	0–2	19°00'N	121°53'W	4138	'Red' clay	<1
Ch.	2	0–4	16°02'N	125°01'W	4354	'Red' clay	<1
Ch.	5	0–4	13°03'N	125°29'W	4450	Radiolarian clay	5
Ch.	7	0–4	11°10'N	125°34'W	4645	Radiolarian ooze	25
Ch.	8	0–4	10°14'N	125°25'W	4720	Radiolarian ooze	25
Ch.	21	6–8	7°06'N	125°31'W	4565	Calcareous ooze	40
Ch.	25	0–4	4°37'N	125°26'W	4480	Calcareous ooze	70
Ck.	1 B	0–4	29°24'N	153°06'W	5664	'Red' clay	<1
Ck.	2	0–4	35°09'N	157°18'W	5627	'Red' clay	<1
Ck.	4	0–5	42°30'N	162°08'W	5399	Buff clay	1
Ck.	6	0–4	46°57'N	164°50'W	5184	Diatomaceous clay	10
Ck.	7	0–5	47°10'N	165°45'W	5050	Silty clay	1
Ck.	8	0–5	53°02'N	176°15'W	3660	Diatom ooze	40
Ck.	9	0–4	52°25'N	176°25'W	3440	Diatomaceous silt	20
Ck.	11	0–4	49°40'N	177°39'W	4850	Diatomaceous silt	10
Ck.	13-3	0–4	44°45'N	173°02'W	4800	Pyroclastic silt	1
Ck.	16	0–4	36°30'N	173°16'W	4195	Calcareous clay	2
Ck.	22	0–5	26°22'N	168°53'W	4450	Calcareous clay	1
Cusp	2 G	0–4	31°05'N	135°24'W	5160	'Red' clay	<1
Cusp	3 G	0–4	40°56'N	125°38'W	3110	Silty clay	5
Cusp	4 G	0–4	39°30'N	125°52'W	3733	Silty clay	1
Cusp	18 G	0–4	35°05'N	142°31'W	5290	'Red' clay	<1
Gui. 23	41		22°20'N	110°50'W	3270	Calcareous silt	2
MP	3	0–6	20°51'N	127°16'W	4373	'Red' clay	<1
MP	7-2	0–2	12°48'N	134°26'W	4750	Radiolarian clay	10
MP	10-2	0–2	4°37'N	140°00'W	4360	Calcareous ooze	50
MP	13-2	0–2	9°09'N	144°26'W	5080	Radiolarian ooze	30
MP	17-1	0–2	14°40'N	151°55'W	5655	Zeolitic clay	2
MP	20-2	0–2	20°27'N	154°55'W	5087	Silty clay	15
MP	23	0–2	19°53'N	164°30'W	4900	Silty clay	<1
MP	24	0–4	19°45'N	166°50'W	5010	Zeolitic clay	1
NEL-H	1	0–4	27°32'N	154°06'W	5706	'Red' clay	<1
NEL-H	14	1–4	24°08'N	156°04'W	4466	'Red' clay	<1
Nth. Hol.	1	0–2	40°31'N	147°59'W	4660	'Red' clay	<1
Nth. Hol.	2	0–4	51°35'N	149°58'W	4480	Silty clay	2
Nth. Hol.	3	0–4	53°23'N	147°14'W	4210	Silty clay	<1
Nth. Hol.	5	0–4	55°08'N	142°55'W	3710	Silty clay	2
Nth. Hol.	8	0–4	48°38'N	157°29'W	5030	Diatomaceous clay	10
Nth. Hol.	9	0–4	40°53'N	155°13'W	5344	Silty clay	1
Nth. Hol.	10	0–2	40°14'N	155°55'W	5030	Silty clay	<1
Nth. Hol.	11	0–4	38°36'N	154°25'W	5096	Silty clay	<1
Nth. Hol.	12	0–4	37°28'N	154°08'W	5582	Silty clay	2
Pion. 22	100 B		29°19'N	117°28'W	4060	Clayey silt	2
Pion. 29	16		37°16'N	123°33'W	3070	Sandy silt	2
Swed.	72	11–13	7°38'S	152°53'W	5015	Zeolitic clay	<1
Swed.	73 B	10–11	4°04'S	152°53'W	5200	Radiolarian clay	20
Swed.	74 B	5–5.5	0°29'S	151°33'W	4575	Calcareous ooze	80
Swed.	75	9–9.5	0°20'N	150°36'W	4400	Calcareous ooze	60
Swed.	76 B	10–11	3°45'N	149°44'W	5155	Calc.-siliceous ooze	50

TABLE 1 (*continued*)

Collector	Core or Sample No.	Depth below sediment surface (cm.)	Latitude	Longitude	Depth (m.)	Sediment type	Percent-wt. biogenous silica in carbonate-free fraction
Swed.	77 B	6–6.5	9°30′N	148°40′W	5384	Radiolarian clay	5
Swed.	83 B	1–1.5	8°40′N	169°28′W	5456	Radiolarian clay	10
Swed.	85 B	1–1.5	5°34′N	172°12′W	5590	Radiolarian ooze	30
Swed.	89	0–6	2°48′S	178°57′W	5465	Radiolarian clay	5
U.W.	110-2	3–4	57°13′N	144°11′W	3770	Clayey silt	1
U.W.	110-23	0–3	54°59′N	155°12′W	2740	Clayey silt	<1
U.W.	110-37	3–4	53°47′N	161°25′W	3975	Clayey silt	5
U.W.	144-1	1–3	49°56′N	136°59′W	3645	Diatomaceous clay	10
U.W.	144-10	0–2	49°04′N	133°00′W	3390	Clayey silt	3

ples were examined is divided into five regions (Areas 1A—4 in fig. 2), on the basis principally of the amounts of biogenous silica in the sediments. It will be obvious that the samples are not sufficiently closely spaced to permit accurate delimitation of the regions, but some broad trends can be discerned.

Area 1A extends north of latitude 42°N, to the coast of Alaska and the southern part (at least) of the Bering Sea. It thus includes part of the northern Pacific belt of diatomaceous sediment indicated on general sediment charts (fig. 1) as diatom ooze. Estimated weight-percentages of biogenous silica in this area range from less than 1 to 10, with percentages greater than 10 only in the two samples from the southern Bering Sea. The siliceous skeletons in the sediment tend to be masked by terrigenous and pyroclastic debris to such a degree that the sediment can hardly be called a true diatom ooze, which according to the usual definition must contain more than 20 percent siliceous skeletal remains.

Area 1B is not precisely delimited from 1A at its northern end, and extends outward from the coast of North America to a distance which cannot be determined on the basis of the scattered samples but which is probably of the order of 100-300 miles. In this region, 1-5 percent of the non-calcareous part of the sediment is made up of diatoms, radiolarians and sponge spicules, and the major portion of the sediment is formed by terrigenous debris. It is possible that higher percentages of biogenous silica might be found in some localities protected from the influx of terrigenous debris.

Area 2 is bounded on the north by 1A, on the east by 1B, and extends south to latitude 13°N, approximately. The sediments of this area are predominantly red clays, usually with less than 1 percent biogenous silica, containing 2 percent in a few samples, and with 15 percent in one sample dominated by pyroclastic debris near the Hawaiian Islands.

Area 3A extends from approximately 13°N latitude to a southern boundary extending WNW-ESE between latitudes 5°S and 15°S. It includes the equatorial system of radiolarian and formaminiferal oozes, with weight-percentages of biogenous silica in the non-calcareous fractions ranging from 5 to 80.

Area 3B is represented by only two samples near latitude 15°S, longitude 115°W. These sediments are superficially similar to the calcareous oozes collected nearby, but contain less than 1 percent biogenous silica in the non-calcareous fraction, compared with values of 10 to 70 percent for adjacent samples.

Area 4 extends southwest of the southern limit of area 3A, and is characterized by red clays (with some calcareous oozes in the eastern part) containing 1 percent or less biogenous silica.

REASONS FOR THE DISTRIBUTION PATTERN

Evidently, the contribution of biogeneous silica to a pelagic sediment at any given locality will depend on the amount of siliceous skeletons produced in the water column supplying the sediment, on the degree to which the biogenous silica is masked by other sedimentary components, and on the extent to which the siliceous skeletons are dissolved during their descent to the sea floor or during their incorporation into the sediment. The relative importance of these and related factors will now be considered, as they affect that part of the Pacific under discussion.

Geographical variation in the amount of biogenous silica produced.—It has long been realized that the production of diatoms is high in high southern and northern latitudes and in areas of upwelling, and that the equatorial region of the Pacific has a particularly rich radiolarian fauna. It is now pertinent to examine more closely the relation between areas of high and low organic production and the biogenous silica content of sediments, a subject which has been discussed for the South Atlantic by Pratje (1951).

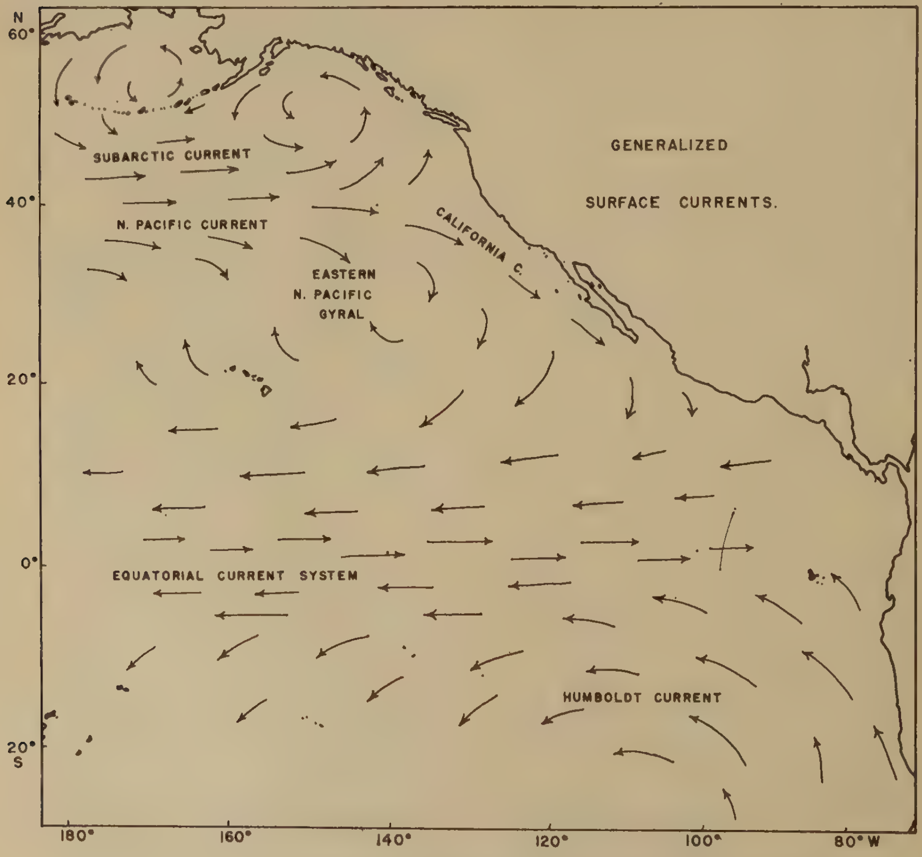
For the part of the Pacific under consideration, there are practically no data on the amounts of radiolarian skeletons produced per unit area and time at various localities, and neither do we have much information of this type about the diatoms. For most parts of the ocean, rates of production of siliceous organisms must be inferred from other measurements such as total plankton volumes, or rates of organic fixation of carbon, and so on, which in a general way indicate biologically rich and biologically poor areas. Some inferences concering organic production can also be drawn from the physical structure and behavior of the water masses in various areas, and from the distribution of nutrient elements in the upper water layers. To facilitate this discussion, the surface currents of part of the Pacific Ocean are shown schematically in fig. 3.

Production of siliceous organisms is high in at least some parts of areas 1A and 1B because of physical mechanisms bringing fresh supplies of nutrients into the photic zone. In area 1A this is effected by the seasonal overturn of the Pacific Subarctic Water, supplemented by nutrient-rich water flowing southward from the Bering Sea, and in area 1B it results from coastal upwelling (Sverdrup *et al.*, 1942). R. W. Holmes (in press) found high organic production in the surface waters in latitudes 50°-55°N, longitudes 155°-180°W, but there are few data on the southern limit of this zone of high production in the northeastern Pacific. This southern limit might be expected to coincide approximately with the boundary between the cold Subarctic Water and the Central Pacific Water, which in longitudes 180°-150°W is found slightly north of the fortieth parallel.

Area 2 coincides approximately with the eastern gyral of the surface currents of the North Pacific. This area is characterized by a pronounced thermocline and stable stratification, so that there is little opportunity for nutrient-rich deeper water to be brought into the photic zone. Holmes (in press) has found that organic production in the surface water along longitude 120°W is considerably lower between latitudes 15°N and 30°N than it is between 15°N and the equator. Along a line running northward between longitudes 170°W and 160°W, Steemann Nielsen and Jensen (1957) found a lower rate of organic production at latitude 13°N and northward than they found at the equator and 4°N. These observations indicate that organic production in an area corresponding at least approximately with area 2 is lower than that further to the north and to the south.

Area 3A corresponds moderately well with the equatorial current system, which is known to be an area of high production of plankton due to the upwelling associated with the divergence near the equator (Cromwell, 1953). King and Demond (1953) and King and Hida (1957) found total zooplankton values indicating that the northern boundary of the equatorial region of high organic production lies at approximately latitudes 8°-12°N. The same authors found also that within the equatorial current system there is at least sometimes a west-east gradient of increasing zooplankton abundance from longitude 180° to 150°W, while the abundance remains approximately constant east of longitude 140°W: this gradient may be reflected in the biogenous components of the sediments. Jerlov (1953), investigating the distribution of particles suspended in the water-column along a line from approximately Lat. 15°N, Long. 165°W to Lat. 3°S, Long. 178°W, found indications that the equatorial belt of high organic production extends from approximately the equator to latitude 14°N, and thus corresponds moderately well with the latitudes of area 3A in these longitudes. The obliquity of the boundary between areas 3A and 4 may result from nutrient-rich cold water being brought by the Humboldt Current into the region bounded approximately by latitudes 5°S and 15°S and longitudes 110°W and 130°W. This hypothesis is supported by the finding of King and Hida (1957) that the total zooplankton values between latitudes 2°S and 10°S were higher along longitude 120°W than along longitude 158°W.

Area 3B differs from 3A in having a much smaller percentage of biogenous silica in the carbonate-free fraction of the sediment, but it appears unlikely that this difference is due entirely to the rate of production of organisms with siliceous skeletons in area 3B being spectacularly less than that in area 3A which adjoins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N. PACIFIC CURRENT
EASTERN
N. PACIFIC
GYRAL
CALIFORNIA C.
GENERALIZED
SURFACE CURRENTS.
EQUATORIAL CURRENT SYSTEM
HUMBOLDT CURRENT

FIG. 3. The general pattern of surface currents in part of the Pacific Ocean. (After Sverdrup *et al*, 1942.)

it to the west, north and north-east. The remains of calcareous organisms are substantially the same in the nearby Capricorn samples 40H, 41H, 40B, and 41B as in the two samples representing area 3B, which seems to indicate that the production of calcareous organisms is not greatly different on either side of the boundary. The difference in content of siliceous skeletons of areas 3A and 3B cannot at present be explained satisfactorily.

The hydrography and biology of area 4 are very incompletely known, but it may be justifiable to regard this region as the southern hemisphere equivalent of area 2. It is not unlikely that the layering of the water masses is relatively stable, and there are no known processes in this region bringing nutrient-rich water from high latitudes or from the subsurface layers. Along a line running northward between longitudes 175°W and 165°W, Steemann Nielsen and Jensen (1957) found much higher rates of organic production at the equator than at latitude 3°S and further south.

A factor which could influence the relation between areas of highly productive surface waters and the biogenous silica content of the sea floor directly below, is lateral transport displacing the skeletons during their descent to the bottom. It is evident that particles falling from the surface are concentrated at mid-depths by pronounced convergences (Jerlov, 1953), and W. Schott (1936) considered that a northward transport of settling diatom frustules is indicated by the fact that the northern boundary of the zone of diatom ooze in the southern Indian Ocean and part of the South Atlantic lies somewhat to the north of the Antarctic Convergence. But the general coincidence of areas of high organic production with sediments containing high proportions of organic remains is evidence that lateral transporting forces do not displace settling skeletal remains over great distances.

Influence of silica from volcanic sources.—The supply of silica from volcanic sources has often been cited (Taliaferro, 1933; Bramlette, 1946) as an important factor in the production of siliceous organisms which subsequently contribute their remains to sediments. While this is undoubtedly an important factor in near-shore environments and enclosed seas, it seems to be of only secondary importance in truly deep-sea environments. In regions of the open ocean in which volcanic islands supply large amounts of volcanic ash to the sea floor, the liberation of silica into the bottom water cannot affect the production of siliceous organisms at the surface unless there is some mechanism to bring the bottom water near the sea surface. And in those parts of the open ocean where deeper water is brought to the surface by upwelling or divergences, the general increase in biological production is dependent on the increased supply not only of silica but of a number of nutrients. In near-shore and enclosed-sea environments, mechanisms bringing deeper water to the surface are more commonly active, and it is here that volcanic enrichment of the water in silica can be an important factor favouring high production of siliceous organisms.

In some sediments, the presence of pyroclastic material probably helps preserve siliceous skeletons from solution after burial. There is evidence from deep-sea sediment cores that siliceous skeletons are slowly dissolved after deposition, especially in localities at which the proportion of biogenous silica to other constituents of the sediment is initially low. In such sediments, the liberation of silica by the weathering of pyroclastic material probably reduces the rate of dissolution of the biogenous opaline silica.

Masking of biogenous silica by other sediment components.—Obviously, the percentage of biogenous silica in the total sediment at any locality will depend on the extent to which the siliceous skeletons are diluted or masked by other sediment components such as terrigenous or pyroclastic debris, calcareous skeletal remains, etc. (fig. 1). Over a large part of area 3A, although the production of siliceous skeletons is apparently high and biogenous silica may constitute up to 80 percent of the non-calcareous portion of the sediments, dilution by calcareous organic remains reduces the proportion of biogenous silica in the total sediments to a very few percent—see, for example, Arrhenius' (1952) estimates of biogenous silica in calcareous oozes collected in the equatorial carbonate belt.

Dilution by terrigenous material is the principal cause of the relatively low percentages of biogenous silica in areas 1A and 1B, despite the high rate of organic production in those areas. And were it not for dilution by pyroclastic material in the only sample examined from near Hawaii (MidPac core no. 20-2), the percentage of biogenous silica in the carbonate-free fraction of that sample would be considerably higher than 15.

Influence of depth.—It is well known (Sverdrup *et al.*, 1942; Revelle, 1944) that depth has a profound effect on the amount of calcareous organic remains in pelagic sediments. There is apparently a 'compensation depth', varying somewhat in different regions, below which calcium carbonate cannot make large contributions to the sediments because the rate of its dissolution exceeds the rate of supply to the sediments. A major factor in this effect of depth is apparently the high carbon dioxide content of the bottom water which originates in high latitudes, and increased hydrostatic pressure is probably also a factor. Some authors (Twenhofel, 1939, p. 366; Correns in Trask, 1939, p. 379) have implied that there may also be a compensation depth for the accumulation of biogenous silica, situated at a greater depth than that for calcium carbonate. There is, however, little evidence to support such a postulation. Jouset and Seczkina (1955) and Bezrukov (1955) have reported diatomaceous sediments from depths as great as 9,394 meters in the Kurile-Kamchatka Trench. The concept of a compensation depth for siliceous organic remains probably resulted from the general coincidence of areas of low biological production with the deeper regions of the ocean.

Depth has of course an indirect effect upon the percentage of biogenous silica in total sediments through its effect on the dissolution of calcium carbonate. If the processes of biological production and sedimentation are identical at two localities which differ only in that one has a depth considerably less than the carbonate compensation depth and the other has a depth considerably greater, then the percentage of biogenous silica in the total sediment will be much less at the former locality than at the latter due to the dilution with calcium carbonate. Also, in a general way shallower depths are found nearer continents, where the supply of terrigenous debris is generally great: thus the contribution of biogenous silica to sediments at these near-shore shallow depths is often low due to masking by terrigenous components.

The influence of rates of deposition.—It seems that a considerable amount of the dissolution of siliceous skeletons takes place while they are lying on the sediment surface, and before they are buried to a depth greater than a few centimeters. Rapid burial probably reduces the rate, and perhaps also the extent, of dissolution of the siliceous skeletons. Areas 1A, 1B, 3A and 3B are characterized in general by high rates of sedimentation as compared to the lower rates of areas 2 and 4. In the areas of high rates of sedimentation most of the siliceous skeletons are well preserved, whereas in areas 2 and 4 many of them show partial dissolution.

CONCLUSION

The foregoing discussion indicates that the pattern of distribution of biogenous silica in the sediments of the part of the Pacific Ocean under consideration is dependent principally on the rate of production of diatoms and radiolarians, which varies from one region to another. A similar dependence was found by Pratje (1951) in his study of siliceous organic remains in sediments of the South Atlantic. Dilution by the rapid accumulation of terrigenous or pyroclastic debris or biogenous calcium carbonate reduces the percentage of biogenous silica in the total sediment, but on the other hand probably tends to protect the siliceous skeletons from dissolution. Depth *per se* seems not to be an important direct factor in the accumulation of biogenous silica, though it has an indirect effect through its influence on the accumulation of calcium carbonate, and through its general increase with increasing distance from terrigenous sediment sources.

REFERENCES

ARRHENIUS, GUSTAF, 1952, Sediment cores from the East Pacific: Repts. Swedish Deep-Sea Exped., v. 5, 227 p., 30 pls.

BEZRUKOV, P. L., 1955, Donnye otlozhenija Kurilo-Kamchatskoj vpadiny (Bottom deposits of the Kurile-Kamchatka Trench): Akad. Nauk. SSSR, Inst. Okeanologii, Trudy, v. 12, pp. 97-129.

BRAMLETTE, M. N., 1946, Monterey Formation of California and origin of its siliceous rocks: U. S. Geol. Survey Prof, Paper 212.

CORRENS, C. W., 1939, Pelagic sediments of the North Atlantic Ocean; in P. D. Trask (ed.) Recent marine sediments, p. 373-395. Tulsa, Oklahoma.

CROMWELL, TOWNSEND, 1953, Circulation in a meridional plane in the Central Equatorial Pacific: Jour. Marine Research, v. 12, pp. 196-213.

DIETZ, R. S., 1955, Manganese deposits on the Northeast Pacific sea floor: California Jour. Mines and Geology, v. 51, no. 3 (July), pp. 209-220.

EHRENBERG, C. G., 1844, Über 2 neue Lager von Gebirgsmassen aus Infusorien als Meeres-Absatz in Nord-Amerika und eine Vergleichlung derselben mit den organischen Kreide-Gebilden in Europa und Afrika: Ber. K. pruss. Akad. Wiss. Berlin, aus dem Jahre 1844, pp. 57-97.

———, 1856. Mikrogeologie: Leipzig.

HOLMES, R. W., (in press), Surface Chlorophyll *a*, Surface primary production, and Zooplankton volumes in the North-Eastern Pacific Ocean: Internat. Council for the Exploration of the Sea, Symposium on measurements of primary production in the sea (Bergen, 1957).

JERLOV, N. G., 1953, Particle distribution in the ocean: Repts. Swedish Deep-Sea Exped., v. 3, fasc. 2, pp. 73-97.

JOUSET, A. P., and SECZKINA, T. V., 1955, Diatomovye vodorosli v otlozhenijakh Kurilo-Kamchatskoj vpadiny (Diatom algae in the deposits of the Kurile-Kamchatka Trench): Akad. Nauk. SSSR, Inst. Okeanologii, Trudy, v. 12, pp. 130-144.

KING, J. E., and DEMOND, J., 1953, Zooplankton abundance in the Central Pacific: U. S. Fish and Wildlife Service, Fishery Bull., v. 54, no. 82, pp. 111-144.

KING, J. E., and HIDA, T. S., 1957, Zooplankton abundance in the Central Pacific, Part 2: idem, v. 57, no. 118, pp. 365-395.

KOLBE, R. W., 1955, Diatoms from Equatorial Atlantic cores: Repts. Swedish Deep-Sea Exped., v. 7, fasc. 3, pp. 151-184, 2 pls.

———, 1957, Diatoms from Equatorial Indian Ocean cores: idem, v. 9, fasc. 1, p. 1-50, 4 pls.

PRATJE, OTTO, 1951, Die Kieselsäureorganismen des Südatlantischen Ozeans als Leitformen in den Bodenablagerungen: Deutschen Hydrograph. Zeitschr., Bd. 4, Heft 1/2, p. 1-6, 1 pl.

REVELLE, R. R., 1944, Marine bottom samples collected in the Pacific Ocean by the Carnegie on its Seventh Cruise: Carnegie Inst., Washington, Pub. 556, Part 1.

———, 1950, Sedimentation and oceanography: Survey of field observations, in 1940 E. W. Scripps Cruise to the Gulf of California: Geol. Soc. America, Memoir 43, pp. 1-6 (part V).

REVELLE, R. R., BRAMLETTE, M., ARRHENIUS, G., and GOLDBERG, E. D., 1955, Pelagic sediments of the Pacific: Geol. Soc. America Special Paper 62, pp. 221-235.

RIEDEL, W. R., 1957, Radiolaria: a preliminary stratigraphy: Repts. Swedish Deep-Sea Exped., v. 6, fasc. 3, pp. 61-96, 4 pls.

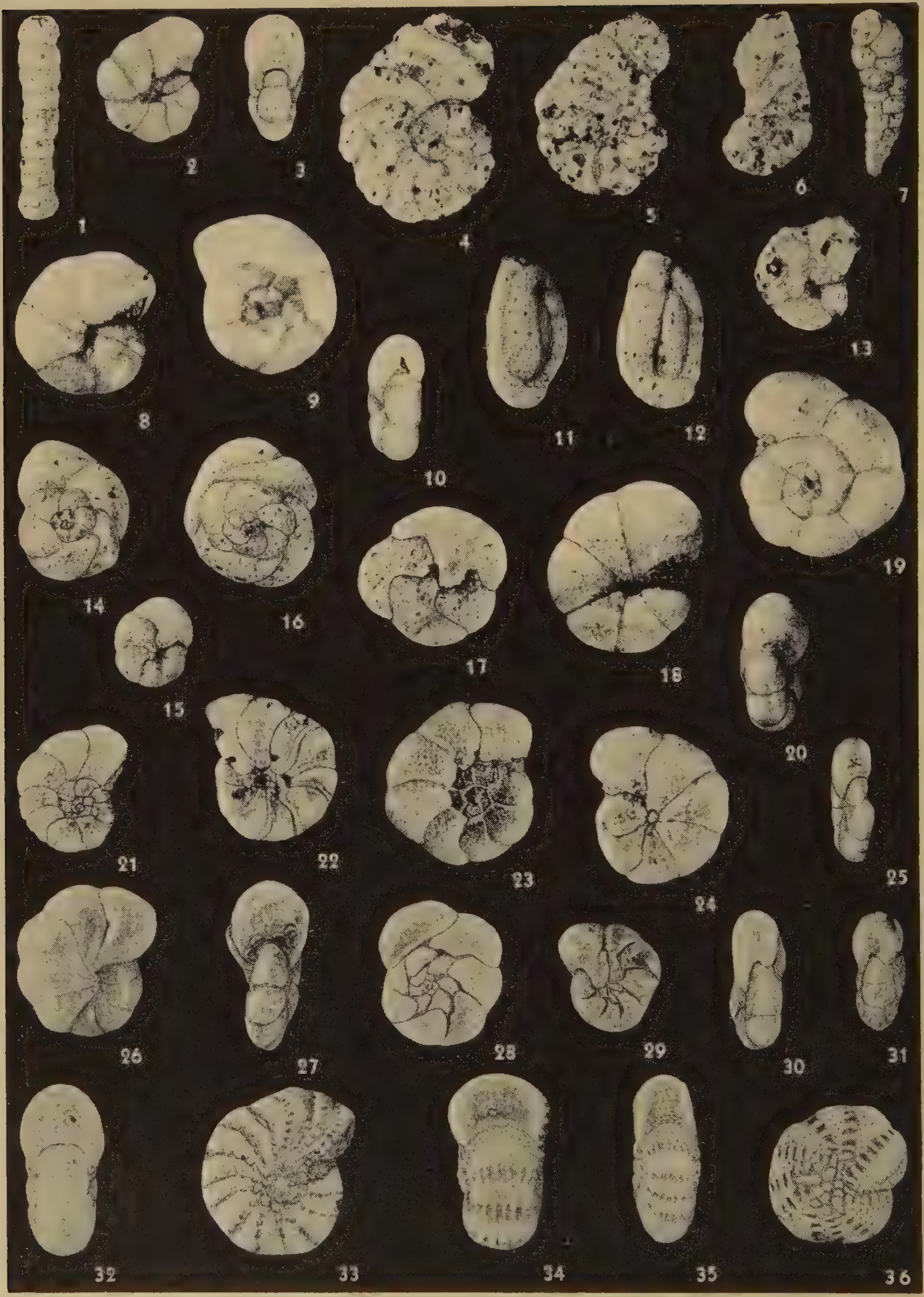
SCHOTT, WOLFGANG, 1936, Rezente Tiefseesedimente in ihrer Abhängigkeit vom Ozeanwasser: in "Stille-Festschrift," Stuttgart.

STEEMANN NIELSEN, E., and JENSEN, E. AABYE, 1957, Primary oceanic production: Galathea Rept. (Danish Deep-Sea Exped.), v. 1, pp. 49-136.

SVERDRUP, H. U., JOHNSON, M. W., and FLEMING, R. H., 1942, The oceans: New Jersey.

TALIAFERRO, N. L., 1933, The relation of volcanism to diatomaceous and associated siliceous sediments: Univ. California Dept. Geol., Sci Bull., v. 23, pp. 1-56.

TWENHOFEL, W. H., 1939, Principles of Sedimentation: McGraw-Hill, New York.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ECOLOGY OF MARSH FORAMINIFERA IN POPONESSET BAY, MASSACHUSETTS

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Abstract—Distributions of the species of Foraminifera (living and dead) forming the greater part of the foraminiferal faunas in marshes in Poponesset Bay, Massachusetts, have been studied. Eight stations were sampled bimonthly for one year (August, 1956 to September, 1957). The marsh environments vary from almost non-marine (with tidal influence) to near marine. *Arenoparrella mexicana*, *Haplophragmoides hancocki*, *Tiphotrocha comprimata*, and *Trochammina macrescens* decrease with increasingly marine conditions, whereas *Jadammina polystoma* and *Trochammina inflata* increase. Other species such as *Ammobaculites dilatatus*, *Ammotium salsum*, *Miliammina fusca*, and *Protelphidium tisburyense* fluctuate independently of the degree of brackish or marine conditions. Unknown factors governing micro- and macroenvironments probably play an important part in controlling distributions. Suggested factors are type of vegetation, chemical factors, pH, nutrients and food. Calcareous specimens are rapidly destroyed after death presumably due either to the ability of the living form to resist acidity or to a postulated increase in acidity immediately below the sediment surface, more probably the latter. This destruction of the tests is of importance in the interpretation of ancient marsh environments. Many species, including the calcareous ones, had their largest living populations in June or September and their smallest in December or February. There were some exceptions such as *Miliammina fusca* which showed an increase in winter. The total living populations were greatest in June and lowest in December, which may be related to maximum temperature and time of greatest reduction in temperature respectively. Multiple sampling showed that distributions at any one station were fairly uniform although nearby samples in different microenvironments in some cases vary considerably.

Explanation of Plate 50

All illustrations were photographed and retouched by the senior author.

Fig. *1*—*Reophax* sp. Station 7. USNM 626397, ×58.
2,3—*Haplophragmoides hancocki* Cushman & McCulloch. *2*, Side view, USNM 626384; and *3*, apertural view, USNM 626385, ×58. Station 2.
4,5—*Ammobaculites dilatatus* Cushman & Bronnimann. Side views, USNM 626373, 626374, ×45. Station 2.
6,13—*Ammotium salsum* (Cushman & Bronnimann). Side views, USNM 626375, 626376, ×58. Station 8.
7—*Textularia earlandi* Parker. USNM 626398, ×58. Station 6.
8–10—*Arenoparrella mexicana* (Kornfeld). *8,9*, Side views, USNM 626377, 626378; and *10*, apertural view, USNM 626379, ×58. Station 2.
11,12—*Miliammina fusca* (Brady). Side views, USNM 626389, 626390, ×45. Station 1.
14–17—*Tiphotrocha comprimata* (Cushman & Bronnimann). *14,16*, Dorsal view, USNM 626399, 626401; and *15,16*, ventral views, USNM 626400, 626402, ×45. Station 1.
18–20—*Trochammina inflata* (Montagu). *18*, Ventral view, USNM 626404, ×45; *19*, dorsal view, USNM 626403, ×58; and *20*, edge view, USNM 626405, ×45. Station 3.
21,22,27—*Jadammina polystoma* Bartenstein & Brand. *21*, Dorsal view, USNM 626386; *22*, ventral view, USNM 626387; and *27*, edge view, USNM 626388, ×58. Station 8.
23–25—*Trochammina macrescens* Brady. *23*, Dorsal view, USNM 626406; *24*, ventral view, USNM 626407; and *25*, edge view, USNM 626408, ×45. Station 1.
26,32—*Protelphidium tisburyense* (Butcher). *26*, Side view, USNM 626391; and *32*, apertural view, USNM 626392, ×58. Station 2.
28–31—*Pseudoeponides anderseni* Warren. *28*, Dorsal view, USNM 626393; *29*, ventral view, USNM 626394; and *30,31*, edge views, USNM 626395, 626396, ×58. Station 6.
33–35—*Elphidium galvestonense* Kornfeld. *33*, Side view, USNM 626380; and *34,35*, apertural views, USNM 626381, 626382, ×45. Station 5.
36—*Elphidium gunteri* Cole. Side view, USNM 626383, ×58. Station 2.

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INTRODUCTION

The purposes of this study were: 1, to investigate the distribution of Foraminifera in marsh environments of varying salinity from almost fresh (with tidal effect) to nearly normal marine and 2, to study the seasonal numerical variation of living specimens of the various species. Eight stations along the marshy shores of Poponesset Bay from the mouth of the narrow portion of the Cotuit River to Meadow Point were sampled bimonthly from August, 1956, to September, 1957. Duplicate samples were taken occasionally to check the reliability of the samples and triplicate samples were taken at the final collection. Salinity and temperature were measured each time of sampling. This study was supported by the University of California under contract with the Office of Naval Research and by the Woods Hole Oceanographic Institution. James R. Moriarty drafted the text figures. Miss Ruth Todd kindly compared specimens of *Ammobaculites dilatatus* with the types.

This is Marine Foraminifera Laboratory Contribution no. 27, Scripps Institution of Oceanography Contribution, New Series, and Woods Hole Oceanographic Institution Contribution no. 971.

DESCRIPTION OF THE AREA

Poponesset Bay is situated on the south side of Cape Cod, Massachusetts, extending roughly from Lat. 41°35′ N to Lat. 41°37′ N and Long. 70°27′ W to Long. 70°28′ W. The upper part of the bay is charted as the Cotuit River but in this study the river is more rigorously defined as the narrow stream draining into the bay at the northern end. The collecting stations (Text-fig. 1) are situated along the eastern shore of the bay from the river mouth to a small marsh east of Meadow Point. The latter is almost directly exposed to the open water of Nantucket Sound owing to the comparatively recent opening of a large gap through the sand spit (Poponesset Beach) which formerly cut this area off from the open sound to the southeast and east. This sand spit and opening are not illustrated since no accurate survey is available.

STATIONS

Eight stations were sampled at approximately bimonthly intervals from August, 1956, to September, 1957. At various times duplicate samples were taken and, at the last collection, triplicate ones. The following is a general description of the environment of each station, including maximum and minimum temperatures and salinities encountered during the collecting period, and the foraminiferal species comprising the major part of the faunas (living plus dead). These temperature and salinity values may not necessarily reflect the extremes which occurred during this interval since the sampling times may not have coincided with them. At no time of sampling was any locality frozen solid although in February there was a thin skin of ice at stations 4, 5, and 8.

Station 1. In *Zostera* on high marsh submerged only at high tide. Located slightly above the river mouth. 1.5°C. (Feb.) to 24°C. (Aug.), salinity 0.6–21.6 ‰. This maximum salinity was observed only once, salinities otherwise did not exceed 9.9 ‰. *Miliammina fusca*, *Tiphotrocha comprimata*, and *Trochammina macrescens* comprise 91% of the fauna.

Station 2. Muddy bank at edge of *Zostera* growth, submerged at mid-tide. Located slightly below the river mouth. 4.5°C. (Dec.) to 26°C. (June), salinity 1.8–28.2 ‰. *Ammotium salsum*, *Arenoparrella mexicana*, *Miliammina fusca*, *Protelphidium tisburyense*, *Tiphotrocha comprimata*, and *Trochammina macrescens* comprise 90% of the fauna.

Station 3. *Zostera* marsh exposed at low tide. 3°C. (Feb.) to 22°C. (Aug.), salinity 4.2–20.6 ‰. *Arenoparrella mexicana*, *Miliammina fusca*, *Tiphotrocha comprimata*, and *Trochammina inflata* comprise 88% of the fauna.

Station 4. Shallow pool in *Zostera* growth about one foot above low tide level. This station was not sampled until December. 1°C. (Feb.) to 22.5°C. (Sept.), salinity 6.2–23.9 ‰. *Ammotium salsum*, *Arenoparrella mexicana*, *Miliammina fusca*, *Protelphidium tisburyense*, *Tiphotrocha comprimata*, and *Trochammina macrescens* comprise 93% of the fauna.

Station 5. Shallow pool (1–4 inches deep) in high marsh behind *Zostera* growth. 1°C. (Feb.), to 32°C. (June), salinity 4.5–24.2 ‰. *Ammotium salsum*, *Jadammina polystoma*, *Protelphidium tisburyense*, *Tiphotrocha comprimata*, and *Trochammina inflata* comprise 92% of the fauna.

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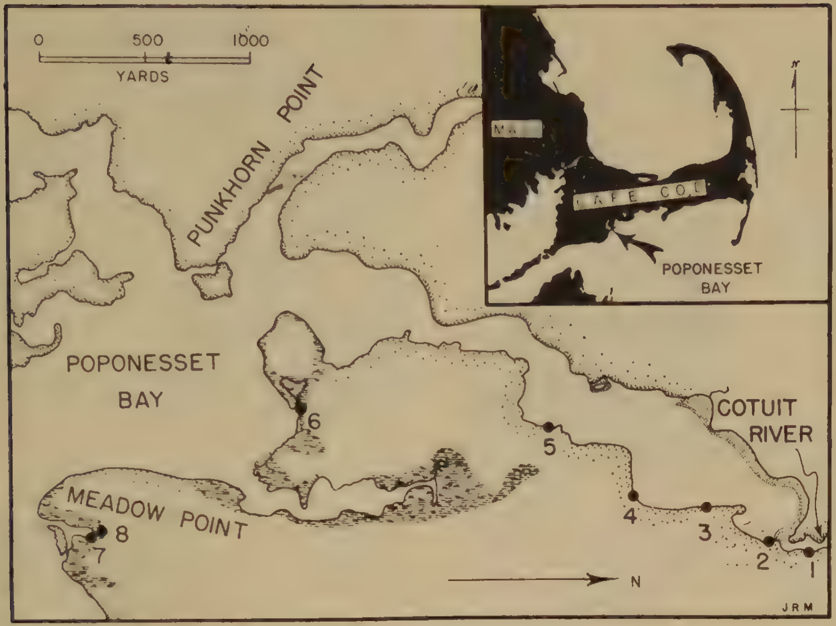


TEXT-FIG. *1*—Location of stations.

Station. 6. High *Spartina* marsh exposed except at high tide. 3.6°C. (Dec.) to 29.5°C. (June), salinity 24.8–28.2 ‰. *Ammotium salsum, Jadammina polystoma, Miliammina fusca,* and *Trochammina inflata* comprise 88% of the fauna.

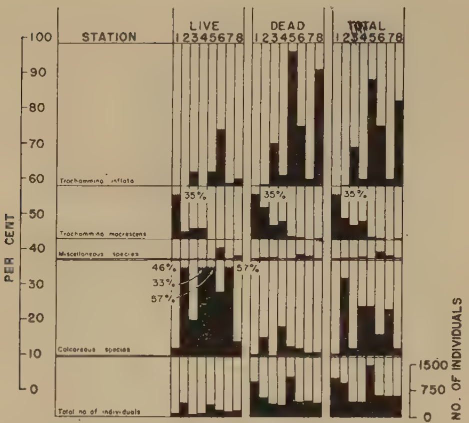
Station 7. High *Zostera* marsh exposed except at high tide. 0.2°C. (Feb.) to 29°C. (June), salinity 23–34.3 ‰. *Ammotium salsum, Miliammina fusca,* and *Protelphidium tisburyense* comprise 90% of the fauna.

Station 8. Inner (landward) end of long, narrow high marsh in shallow pool or channel (1–6 inches deep), isolated except at high tide and not flushed by every tide. 0.2°C. (Feb.) to 30°C. (Aug., June), salinity 26.5–45.2 ‰. The salinity only reached this high value at one time of sampling, otherwise the maximum was 35.8 ‰. *Ammotium salsum, Jadammina polystoma,* and *Trochammina inflata* comprise 88% of the fauna.

In most places the highest temperatures were registered in June, the lowest in February. The salinity changes did not follow any regular seasonal pattern probably due to the many factors involved such as tidal influence, rainfall, seepage, evaporation, etc. Station 5, which shows a lower salinity minimum than station 4 nearer the river, may be affected by fresh water seepage from the high bank lying behind it. The high salinity registered at station 8 may be due to evaporation since the locality is apparently not reached by all high tides.

METHODS OF STUDY

The samples were collected by pushing a piece of plastic tubing (internal diameter 3.3 cm.) into the sediment. A constant volume sample one centimeter thick was taken from the upper part of the core using the method described by Walton (1955). The fluid condition of the mud in many cases made it difficult to be certain that equal volume samples were obtained by this method. The area of sediment surface collected, however, was constant. The samples were preserved with buffered formalin and a small quantity of sodium bicarbonate was added, since it has been found that buffered formalin and sea water become increasingly acid with time. Occasional samples giving an acid reaction were discarded before laboratory study. The samples were washed through a



Text-fig. *2*—Average frequency distributions (% of living, dead, and total) of foraminiferal species at each station.

sieve (average openings 0.062 mm.), stained with rose Bengal and examined while wet, which is necessary since many specimens of marsh species are destroyed or badly distorted upon drying. It was found that much of the organic detritus could be eliminated by using a pick and then decanting several times.

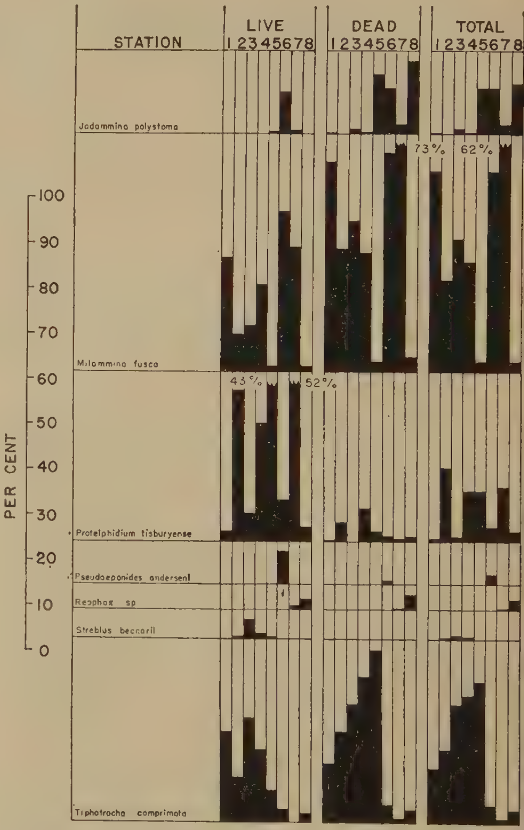
To determine distributional patterns at each station (Text-figs. 2–4) all samples, regardless of season, were averaged. Multiple samples at any one station were averaged first. Each species is plotted in percents of living, dead, and total populations. Occurrences of less than 0.1% are omitted so that a species which may occur very rarely appears to be absent. Some of these rare occurrences are mentioned in the "systematic descriptions."

The data for all stations were averaged to determine the seasonal distributions of the living species. These are given (Text-fig. 5) in numbers of specimens since the area of sampling is constant and it is assumed that the living population is sampled *in toto*.

DISTRIBUTION OF SPECIES

Environmental.—By averaging the data for all seasonal samples taken at each station it is believed that any irregularities of collection are smoothed out and a general picture at any locality obtained. The diagrams (Text-figs. 2–4) include species distributions of dead and total populations, which are of the most interest to the paleontologist, as well as the living populations.

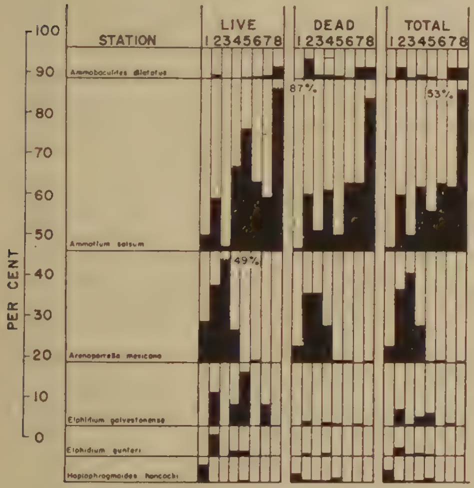
The following generalizations can be made on the distributional patterns, when progressing from the least to the most nearly marine conditions. *Arenoparrella mexicana*, *Haplophragmoides hancocki*, *Tiphotrocha comprimata*, and *Trochammina macrescens*, which form relatively high percentages of the populations at the lower salinity stations, are much rarer at the more marine stations. On the other hand, *Jadammina polystoma*, *Reophax* sp. and *Trochammina inflata*, which are absent or very rare at the low salinity stations, are abundant at the more marine ones. Whether or not these



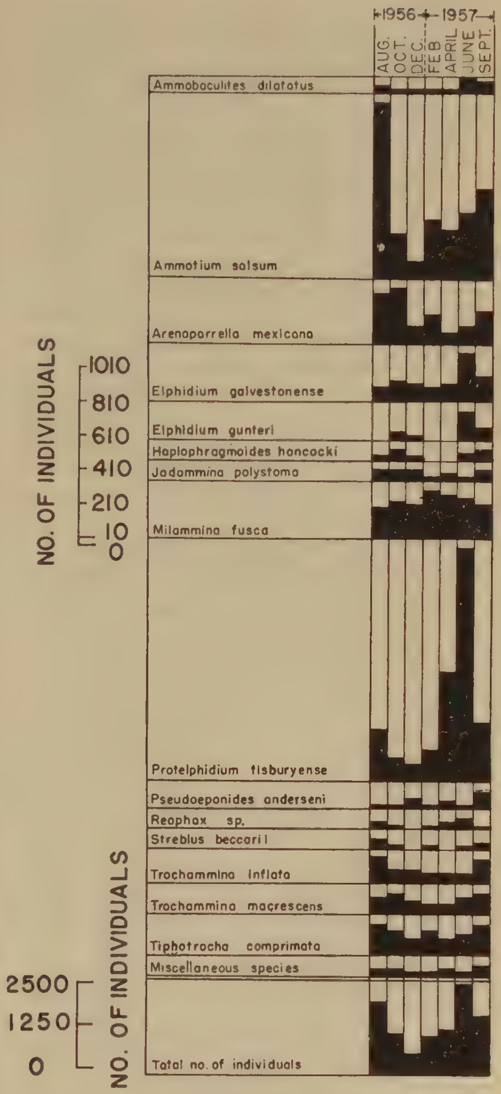
Text-fig. *3*—Average frequency distributions (% of living, dead, and total) of foraminiferal species at each station.

differences in distributions are related to differences in salinity conditions is an open question. Other factors may be involved such as changes in vegetation, differences in pH at the sediment surfaces under varying saline conditions, and chemical nutrients or food introduced by the fresh water.

Ammobaculites dilatatus, *Ammotium salsum*, *Elphidium galvestonense*, *E. gunteri*, *Miliammina fusca*, and *Protelphidium tisburyense* appear to fluctuate, for the most part, independently of the salinity or related factors. *Ammotium salsum*, common at most stations, is very abundant at station 8. Perhaps this is due to its apparently high tolerance of varying conditions. It will be noted that it forms a much higher percent of the living population than of the dead population, whereas *Jadammina polystoma* and *Trochammin inflata*, which are fairly abundant in the dead population, form a very small part of the living one. This leads to the speculation that conditions adverse to the latter two species have occurred and the more tolerant form has flourished. The high salinity of 45.2 °/₀₀ found in April is a clue to what one of these adverse conditions may be. *Miliammina fusca*, which occurs at very low frequencies at stations 5 and 8, apparently prefers an environment which is periodically exposed because of tidal action. The fluctuations of *Ammobaculites dilatatus*, the two species of *Elphidium*, and *Protelphidium tisburyense* are not easily explained by the known characteristics of the



TEXT-FIG. 4—Average frequency distributions (% of living, dead, and total) of foraminiferal species at each station.



TEXT-FIG. 5—Seasonal frequency distributions (actual number of living specimens) of foraminiferal species at all stations. (Note change of scale after the first 10 individuals.)

environments. In general, the three calcarious species follow the same pattern, being present or most common at stations 2, 4, 5, and 7. Thus, they are adapted to both non-marine and near marine conditions and to environments which may or may not be partly exposed due to tidal action.

Of the remaining two species illustrated in the bar diagrams, *Pseudoeponides anderseni* is confined to station 6 (a few dead specimens at station 4) and is discussed more fully in the systematic section; *Streblus beccarii* is too rare in the area for a reliable analysis of its preferences. It is most common at station 3 and was not found at stations 1 and 6–8 suggesting that it prefers intermediate conditions between non-marine and marine. It is possible, however, that marsh environments are not favorable for this species and its distribution is mainly confined to other environments

In addition, most species appear to favor certain microenvironments. This is discussed further in the section on multiple sampling. The species forming the major part of the faunas at each station are listed in the station descriptions.

Calcareous species.—A study of the bar diagrams (Text-figs. 2–4) shows that the calcareous species are represented for the most part by living specimens. Very few dead ones were observed. This leads to the inference that below the sediment surface, or perhaps even at the sediment-water interface, the pH is sufficiently low to cause the dissolution of the tests. If this condition exists in the "living environment" of the species they must have some mechanism to resist the acidity. Since this implies the expenditure of considerable energy on the part of the organism, it seems more probable that the increase in acidity occurs immediately below the sediment surface, probably due to decaying vegetation, and that it is here that the solution of the tests occurs. It should be remembered that the samples represent only the upper centimeter of sediment so that this supposed acidity increase must occur very near the surface. No reliable measurements have been taken in marsh sediments to show this postulated change in pH across the sediment-water interface. Stewart (1956) found pH values of 7.45 and 6.79 at depths of 15–20 cm. and 23–28 cm. respectively in two marsh cores from San Miguel Lagoon in Baja California. Similar or even lower values have also been observed by others in marsh sediments. Such acidity is more than sufficient to dissolve the calcium carbonate tests.

This rapid solution of the calcareous tests in marsh sediments means that ancient marsh sediments in the sedimentary column may not contain the calcareous species. This must be taken into consideration in interpreting ancient environments by comparison with those of the present day.

Seasonal.—The bar diagram (Text-fig. 5) illustrates the occurrence of living specimens of each species for each season. Some species show a decided increase at certain seasons which suggests that reproduction increases, or mainly occurs, at such times. Examples of this are *Ammotium salsum* (August), *Elphidium galvestonense* (June, September), and *Protelphidium tisburyense* (June). The peak of the standing crop may, of course, have occurred before or after the month where it appears but must have been later than the previous collecting date and before the following one.

Other species such as *Jadammina polystoma*, *Tiphotrocha comprimata*, and *Trochammina macrescens* apparently maintain a fairly steady production, although showing a slight decrease in the winter months. *Miliammina fusca* shows a slight increase in winter. The standing crops taken as a whole are largest in June and lowest in December. An interesting correlation can be made with the temperatures obtaining at these seasons. If the temperatures at the various stations are averaged for each season the results are as follows: August (1956) 24.5°C., October 17.9°C., December 4.9°C., February (1957) 1.6°C., April 17.7°C., June 26.3°C., and September 21.9°C. Thus, during this particular time interval, the standing crop was highest at the time of highest temperature and lowest following the greatest *fall* in temperature, rather than at the time of minimum temperature. Laboratory studies by Myers (1935) and Bradshaw (1955) show that reproduction in certain species increases at higher temperatures and so it may be inferred that the increased standing crop found in summer is due to increased production at that time.

Multiple sampling.—At the final collecting period (September, 1957) triplicate samples were taken at each station, usually within about six inches of each other. This was done to check the reliability of the sampling. The results were very reassuring although occasional discrepancies occurred, usually in the frequency of living specimens of a single species. The total number of living specimens, however, was surprisingly uniform, the larger fluctuations occurring in the numbers of dead specimens. This strengthens the validity of the assumption that the living populations were sampled *in toto*.

A duplicate sample taken near station 5 in December apparently represents a different microenvironment from that of station 5 itself. Unlike the other samples from that station, which were taken in a shallow pool, it was taken from sediment in the *Zostera* growth. The fauna differs in the much larger population of living *Ammotium salsum*, *Haplophragmoides hancocki*, *Miliammina fusca* (previously mentioned as apparently preferring an environment partially exposed during the tidal cycle), and *Trochammina inflata* and the smaller populations of living *Elphidium galvestonense* and *Protelphidium tisburyense*. The environmental factors involved, aside from the partial exposure, may be differences in salinity and other chemical factors (note the unusually low salinity registered at times in the pool at station 5), food supply, competition of rival organisms, etc. A detailed study should be made to define the factors affecting such microenvironmental differences. This would probably involve, in addition to measurements of the physical characteristics, a study of the vegetation and organisms found in the various communities. Bacterial activity is probably of great importance. This particular example also emphasizes the danger of drawing conclusions from isolated samples.

SYSTEMATIC DESCRIPTIONS

Sixteen species which comprise most of the foraminiferal fauna in the area are discussed, together with a brief résumé of the distribution pattern. It should be realized that where the largest living population of any species is said to occur at any given collection it may actually have occurred earlier or later but not as early as the preceding collection or as late as the following one.

In addition, there are a few species (included with "miscellaneous species" in Text-figs. 4, 5) which are worth mentioning. One is a very small, smooth, thin-shelled *Miliolinella* which occurs rarely at stations 3–5 and somewhat more commonly at stations 6 and 8. Like the other calcareous species, most specimens were living. Members of the "*Trochammina squamata*" Parker and Jones group occurred rarely. Occasional specimens of *Saccodendron* were observed in most samples. Thecamoebina were observed at station 1.

The figured specimens have been deposited at the U. S. National Museum, Washington, D. C.

Order FORAMINIFERA

Family REOPHACIDAE

REOPHAX sp.

Pl. 50, fig. 1

This species appears to be new but due to its fragility most of the specimens found were broken. For this reason it is left unnamed until a good suite of material can be obtained. The figured specimen, one of the few unbroken forms, has ten chambers including a relatively large proloculus. The cross section is circular, as is the aperture. The sutures are very slightly depressed and, since the chambers do not increase in size as added, the test is almost straight sided with a bulging proloculus. Length of figured specimen 0.58 mm.

Distribution.—Very rare at many stations but reaches frequencies greater than 0.1% only at stations 7 and 8 (up to 2% of total at station 8). The largest living population appeared to be in June but there were too few living specimens for a reliable statement.

Family LITUOLIDAE

HAPLOPHRAGMOIDES HANCOCKI Cushman & McCulloch

Pl. 50, figs. 2,3

Haplophragmoides hancocki CUSHMAN & MCCULLOCH, 1939, Allan Hancock Pacific Expeds., v. 6, no. 1, p. 79, pl. 6, figs. 5,6.

This species was described from a sample collected from off the wharf at Ketchikan, Alaska, in which numerous representatives of the Thecamoebina also were found, showing that there must have been contamination by river forms. Reported occurrences

(125)

farther south by Cushman & McCulloch should be viewed with some doubt since this species is probably not a truly marine form.

Distribution.—At stations 1–5, most commonly at station 1 (3% of total). The largest living populations were found in September and October, but so few living specimens occurred that this may not be a reliable observation.

AMMOTIUM SALSUM (Cushman & Bronnimann)
Pl. 50, figs. 6,13

Ammobaculites salsus CUSHMAN & BRONNIMANN, 1948, Cushman Lab. Foram. Research, Contr., v. 24, p. 16, pl. 3, figs. 7–9.
Ammoscalaria fluvialis PARKER, 1952, Mus. Comp. Zoology, Bull., v. 106, no. 10, p. 444, pl. 1, figs. 24,25.

The specimens are slightly thicker than the types from Trinidad. Parker's (1952) observations that the septa are like those of the genus *Ammoscalaria* Höglund (straight, chitinous) are now believed to be erroneous. Further study shows that although very thin when viewed in clarifying oil, the septa are not straight but curved as in the genus *Ammotium* Loeblich & Tappan.

Distribution.—At all stations, most commonly stations 2, 4–8 (up to 17% of total except at station 8, 53%). The largest living population was found in August, the lowest in December.

AMMOBACULITES DILATATUS Cushman & Bronnimann
Pl. 50, figs. 4,5

Ammobaculites dilatatus CUSHMAN & BRONNIMANN, 1948, Cushman Lab. Foram. Research, Contr. v. 24, p. 39, pl. 7, figs. 10,11.

Specimens were compared with the types by Miss Ruth Todd. She reports (personal communication) that the Poponesset specimens are identical with at least one paratype but otherwise are more inflated. This inflation makes the umbilicus more depressed, the sutures more incised, the chambers more distinct, and the periphery more lobulated. The difference, however, is essentially a minor one and does not seem sufficient for specific or subspecific differentiation.

Distribution.—At all stations, most commonly stations 2, 7, and 8 (3% of total). The largest living population was found in June, the lowest in April. Few living specimens were observed at any time at station 7 which is strange in view of the relatively large dead populations found there. These stations, although subject to a high variation of salinity, are all out of water during part of the tidal cycle.

ARENOPARRELLA MEXICANA (Kornfeld)
Pl. 50, figs 8–10

Trochammina inflata (MONTAGU) var. *mexicana* KORNFELD, 1931, Dept. Geology Stanford Univ., Contr., v. 1, no. 3, p. 86, pl. 13, fig. 5.

The specimens are typical.

Distribution.—At all stations except station 7, most common at stations 1–4 (up to 22% of total). This species apparently prefers the less marine localities. The largest living population was found in October, although the numbers for August were almost as high. There was a considerable increase between December and February after which the numbers dropped off again.

Family TEXTULARIIDAE
TEXTULARIA EARLANDI Parker
Pl. 50, fig. 7

Textularia elegans LACROIX, 1932 (*non Plecanium elegans* HANTKEN, 1868), Instit. Ocean., Monaco, Bull., no. 591, p. 8, text-figs. 4–6.
Textularia tenuissima EARLAND, 1933 (*non. T. tenuissima* HÄUSLER, 1881), Discovery Repts., v. 7, p. 95, pl. 3, figs. 21–30.
Textularia earlandi PARKER, 1952, Mus. Comp. Zoology, Bull., v. 106, no. 10, p. 458 (footnote).

This species is included under "miscellaneous species" in the bar diagrams (Text-figs. 4,5). Its occurrence is of interest since it is found only at stations 6–8, indicating that near marine conditions may be required. No living specimens were found except in September and October.

Family RZEHAKINIDAE
MILIAMMINA FUSCA (Brady)
Pl. 50, figs. 11,12

Quinqueloculina fusca BRADY, 1870, *in* BRADY, G. S., & ROBERTSON, Ann. Mag. Nat. Hist., s. 4, v. 6, p. 286, pl. 11, figs. 2a–c, 3.

There is some variation in the smoothness of the test. Smooth-walled individuals, however, are rare.

Distribution.—An ubiquitous marsh form, occurring at all stations at very high fre-

(126)

quencies (up to 62% of total) except at stations 5 and 8 (2%). The latter stations are in shallow pools which are never exposed during the tidal cycle suggesting that the species prefers partially exposed environments. The largest living population was found in February, the smallest in August. The production is presumably fairly high throughout the year to account for the large number of living specimens always present.

Family TROCHAMMINIDAE

TIPHOTROCHA COMPRIMATA (Cushman & Bronnimann)

Pl. 50, figs. 14–17

Trochammina comprimata CUSHMAN & BRONNIMANN, 1948, Cushman Lab. Foram. Research Contr., v. 24, p. 41, pl. 8, figs. 1–3.

Adult specimens have very irregular chambers (figs. 16,17) but the juvenile stages are regular (figs. 14,15).

Distribution.—At all stations, most abundantly at stations 1–5 (up to 31% of total) suggesting that marine conditions are adverse. The largest living populations were found in August and September.

TROCHAMMINA INFLATA (Montagu)

Pl. 50, figs. 18–20

Nautilus inflatus MONTAGU, 1808, Test. Brit., Supp., p. 81, fig. 3.

Distribution.—At all stations except station 1. The highest frequencies are at stations 3, 5, 6, and 8 (up to 30% of total). The largest living population was found in August, the smallest in February, although in April and June living populations were almost as low.

TROCHAMMINA MACRESCENS Brady

Pl. 50, figs. 23–25

Trochammina inflata (MONTAGU) var. *macrescens* BRADY, 1870, *in* BRADY, G. S., & ROBERTSON, Ann. Mag. Nat. Hist., s. 4, v. 6, p. 290, pl. 11, figs. 5a–c.

The possible relationship of this species with *Jadammina polystoma* is discussed under the latter.

Distribution.—Occurs at all stations except station 7. The highest frequencies are found at stations 1–4 (up to 35% of total at station 1) suggesting that this species prefers a non-marine environment. The largest living populations were found from August to October.

JADAMMINA POLYSTOMA Bartenstein & Brand

Pl. 50, figs. 21,22,27

Jadammina polystoma BARTENSTEIN & BRAND, 1938, Senckenbergiana, Band 20, n. 5, p. 381, text-figs. 1–3.

It is possible that this species and *Trochammina macrescens* are related or even identical. *J. polystoma* differs in the less massive test, which is usually more compressed, and in the presence of supplementary apertures on the apertural face. Boltovskoy (1958) postulates that the presence of supplementary apertures on the apertural face of *Protelphidium tisburyense* is a modification due to environmental conditions and does not imply specific difference from specimens without these apertures. It is possible that in a similar manner *J. polystoma* may be a modified form of *T. macrescens* although when the two occur together the adults are easily distinguished. This hypothesis may be tested eventually by culturing in the laboratory.

Distribution.—Rare at stations 1, 3, and 4; somewhat more common at station 7; very common at stations 5, 6, and 8 (up to 11% of total). The species apparently prefers the more marine environments. The largest living populations were found from September to December, but since the number of living specimens was very small even at those times this may not be a reliable observation.

Family ROTALIIDAE

PSEUDOEPONIDES ANDERSENI Warren

Pl. 50, figs. 28–31

Pseudoeponides anderseni WARREN, 1957, Cushman Found. Foram Research, Contr., v. 8, p. 39, pl. 4, figs. 12–15.

Valvulineria sp. PHLEGER & WALTON, 1950, Am. Jour. Science, v. 248, p. 285, pl. 2, fig. 22a,b.

Hofker (1958) suggests that the genus *Pseudoeponides* Uchio is closely related to the genus *Streblus* Fischer. In the Poponesset Bay samples care had to be taken not to mistake specimens of this species for some of the variant forms of *Streblus beccarii*. Especially in wet samples, the dorsal openings are not always immediately observed. *Pseudoeponides anderseni* is also distinguishable by the prolongation of the final chamber which forms a lobe over the umbilical region. This resemblance is mentioned here because it seems possible, in view of the few reported occurrences of *E. anderseni*, that it has not been differentiated from *Streblus beccarii* by some workers.

Distribution.—At station 6 (2% of total). A few dead specimens were observed at station 4 (too few to be included in Text-fig. 3). The species seems to prefer environments having near-marine characteristics (minimum salinity at station 6 was 24.8 °/₀₀). Phleger and Walton (1950) found it only in the high marsh at Barnstable, Mass. (minimum salinity 25 °/₀₀). What the other requirements are which confine this species to such a limited occurrence are not known.

STREBLUS BECCARII (Linné)

Nautilus beccarii LINNÉ, 1758, Test. Brit., Supp., p. 710.

Specimens of this species are usually very small, although at station 1 large specimens were found previous to the current collecting period. In general, the marshes in this area do not seem favorable for the development of the species.

Distribution—At stations 2–5 (up to 0.7% of total). The living population was largest in August. Few living specimens were found except in August and September.

Family ELPHIDIIDAE

PROTELPHIDIUM TISBURYENSE (Butcher)

Pl. 50, figs. 26,32

Nonion tisburyensis BUTCHER, 1948, Cushman Lab. Foram. Research, Contr., v. 24, p. 22, text-figs. 1–3.

This species has a radiate wall structure (personal communication, M. N. Bramlette) and sometimes shows rudimentary retral processes. It is referred to *Protelphidium* because of its affinity with many species referrable to that genus. *Protelphidium* is placed in the family Elphidiidae, although it was originally included with the Nonionidae (Haynes, 1956, p. 86), because the structure of the wall appears to be a fundamental character of more importance in the classification of family groups than such morphological characters as sutural pores or retral processes. As pointed out by Boltovskoy (1958, p. 18) specimens sometimes occur with supplementary apertures on the apertural face, although in Popponesset Bay such specimens are rare and none was observed with more than one such aperture. In counting, however, not every specimen was closely examined for this feature.

Distribution.—At all stations, most commonly stations 2, 4, 5, and 7 (up to 16). It appears to be less adapted to extreme salinities (and/or accompanying factors) being less common at stations 1 and 8. The largest living population was in June, the smallest in December.

ELPHIDIUM GALVESTONENSE Kornfeld

Pl. 50, figs. 33–35

Elphidium gunteri COLE var. *galvestonensis* KORNFELD, 1931 (part), Dept. Geology Stanford Univ., Contr., v. 1, no. 3, p. 87, pl. 15, fig. 1 (not figs. 2,3).

Elphidium galvestonense KORNFELD, PARKER, PHLEGER & PEIRSON, 1953, Cushman Found. Foram. Research, Special Pub. 2, p. 7, pl. 3, figs. 15,16.

The specimens are very variable in the amount of inflation of the chambers. In edge view the umbo often appears to be depressed (fig. 34) rather than protruding as in the typical form. Specimens of other species of *Elphidium* may have been included occasionally in the population counts of this species.

Distribution.—At stations 2, 3–5, and 7; most commonly at stations 2, 4, and 5 (up to 4% of total). The largest living population was in June, the smallest in August and February.

ELPHIDIUM GUNTERI Cole

Pl. 50, fig. 36

Elphidium gunteri COLE, 1931, Florida State Geol. Survey, Bull. 6, p. 34, pl. 4, figs. 9,10; PARKER, PHLEGER & PEIRSON, 1953, Cushman Found. Foram. Research, Special Pub. 2, p. 8, pl. 3, figs. 18,19.

The specimens are usually very small although occasionally larger ones (up to 0.47 mm.) occur. Most of them have about ten chambers in the final whorl instead of 14. In other respects they are typical.

Distribution.—At stations 2–5; most commonly at station 2 (2% of total). The largest living population was in June, with few or no living specimens observed during the rest of the year.

REFERENCES

Boltovskoy, Esteban, 1958, The foraminiferal fauna of the Rio de la Plata and its relation to the Caribbean area: Cushman Found. Foram. Research, Contr., v. 9, p. 17–21, pl. 6.

Bradshaw, J. S., 1955, Preliminary laboratory experiments on ecology of foraminiferal populations: Micropaleontology, v. 1, p. 351–358.

Haynes, John, 1956, Certain smaller British Paleocene Foraminifera, Part I: Cushman Found. Foram. Research, Contr., v. 7, p. 79–101, pls. 16–18.

Hofker, Jan, 1958, The taxonomic position of the genus *Pseudoponides* Uchio, 1950: Cushman Found. Foram. Research, Contr., v. 9, p. 46–48.

Myers, E. H., 1935, The life history of *Patellina corrugata* Williamson, a foraminifer: Scripps Instit. Oceanography, Univ. California, Tech. ser., v. 3, no. 15, p. 355–392, pls. 10–16.

Parker, F. L., 1952, Foraminiferal distribution in the Long Island Sound-Buzzards Bay area: Mus. Comp. Zoology, Bull., v. 106, no. 10, p. 428–473, pls. 1–5.

Phleger, F. B. & Walton, W. R., 1950, Ecology of marsh and bay Foraminifera, Barnstable, Mass.: Am. Jour. Science, v. 248, p. 274–294, pls. 1,2.

Stewart, H. B., Jr., 1956, Sediments and the environments of deposition in a coastal lagoon: Doctoral Thesis, Univ. of California, Los Angeles, 355 p.

Walton, W. R., 1955, Ecology of living benthonic Foraminifera, Todos Santos Bay, Baja California: Jour. Paleontology, v. 29, p. 952–1018, pls. 99–104.

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Heat-Flow Values from the South-Eastern Pacific

PRIOR to these new measurements, twenty-five heat-flow values from the Pacific Ocean Basin and eight from the Atlantic have been published[1]. The surprising fact brought out by these measurements is the approximate equality of average heat flow of the oceanic and continental areas, about $1 \cdot \times 10^{-6}$ cal./cm.^{2} sec. This result was unexpected on the basis of values of radioactivity indicated for typical continental and oceanic crustal rocks existing near the Earth's surface. It has usually been assumed that most of the surface heat flow in continental regions must originate in the relatively thick and radioactive continental crust. Under the oceans, nearly all the average heat flow must come from the mantle beneath the relatively thin oceanic crust.

The new heat-flow values from the Pacific were obtained during October 1957–February 1958 on the Scripps Institution of Oceanography *Downwind* International Geophysical Year Expedition. The measurements are listed in Table 1, and the geographical distribution of stations, with generalized 4,000- and 5,000-m. bottom-depth contours of the area, is shown in Fig. 1. The topography was kindly supplied by Dr. Henry Menard of the Scripps Institution of Oceanography. The field technique was to measure the temperature gradient in the upper few metres of ocean floor sediment with apparatus first described by Revelle and Maxwell[2], and also the thermal conductivity of a cored sample of this sediment by a transient method[1]. The resulting heat-flow values are most probably accurate within 10 per cent, unless otherwise noted. The 'less than' or 'greater than' signs indicate the uncertainty of imperfectly functioning apparatus, usually due to an uncertainty of depth of penetration of the temperature gradient probe into the ocean floor. The thirty-six new measurements comprise a relatively more detailed study in a somewhat limited area, compared to the previous measurements.

When the new heat-flow values are considered together with the previous measurements in the Pacific, some interesting features can be seen. (1) The East Pacific Rise, a broad elevated region of the eastern Pacific sea floor, appears to be associated with a relatively narrow band of high heat flow for at least 6,000 km. along its length. This was indicated by three stations of the previous Pacific measure-

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Table 1. HEAT-FLOW MEASUREMENTS

Station No.	Heat flow (10^{-6} cal./cm.^{2} sec.)	Depth (m.)	Latitude	Longitude	Station No.	Heat flow (10^{-6} cal./cm.^{2} sec.)	Depth (m.)	Latitude	Longitude
1	0·14	4,450	1° 23′ S.	131° 31′ W.	19	1·07	3,700	12° 54′ S.	78° 06′ W.
2	$0{\cdot}52 < Q < 0{\cdot}78$	4,510	14° 59′ S.	136° 01′ W.	20	0·17	5,950	12° 38′ S.	78° 38′ W.
3	0·97	4,760	21° 40′ S.	147° 41′ W.	21	0·17	5,900	12° 59′ S.	78° 21′ W.
4	1·1	5,120	40° 37′ S.	132° 52′ W.	22	0·26	4,220	18° 26′ S.	78° 16′ W.
5	0·14	4,620	42° 16′ S.	125° 50′ W.	23	0·98	3,090	18° 20′ S.	79° 21′ W.
6	0·73	4,140	46° 44′ S.	123° 18′ W.	24	1·02	4,230	19° 01′ S.	81° 29′ W.
7	2·06	3,180	44° 27′ S.	110° 44′ W.	25	2·12	3,880	27° 04′ S.	88° 53′ W.
8	3·06	3,180	43° 43′ S.	107° 33′ W.	26	0·23	3,200	28° 00′ S.	96° 20′ W.
9	2·09	3,850	43° 44′ S.	104° 25′ W.	27	4·54	2,910	27° 55′ S.	106° 57′ W.
10	2·30	4,580	42° 44′ S.	96° 03′ W.	28	$1{\cdot}64 < Q < 1{\cdot}89$	3,500	23° 15′ S.	117° 48′ W.
11	1·0	3,310	41° 06′ S.	86° 38′ W.	29	7·66	3,060	14° 44′ S.	112° 06′ W.
12	$>0{\cdot}89$	4,110	23° 23′ S.	72° 10′ W.	30	1·01	3,580	13° 30′ S.	108° 31′ W.
13	0·80	3,750	23° 28′ S.	72° 58′ W.	31	8·09	3,280	11° 39′ S.	109° 48′ W.
14	1·62	4,550	21° 33′ S.	79° 09′ W.	32	7·95	2,840	9° 55′ S.	110° 39′ W.
15	0·79	2,340	20° 49′ S.	81° 08′ W.	33	0·87	4,040	5° 56′ S.	112° 29′ W.
16	1·54	2,400	20° 48′ S.	81° 09′ W.	34	1·71	4,330	3° 40′ S.	114° 13′ W.
17	1·46	4,440	13° 35′ S.	79° 09′ W.	35	0·56	3,810	1° 28′ N.	116° 04′ W.
18	2·72	2,260	12° 49′ S.	77° 53′ W.	36	0·43	4,200	4° 06′ N.	115° 41′ W.

ments[1], and is represented by stations 7, 8, 9, 10, 27, 29, 31 and 32 of the present study. (2) The axes of the trenches bordering the eastern Pacific Ocean appear to be associated with low heat flow. The previous Pacific measurements indicated this for the trench off Central America. Stations 18, 19, 20 and 21 respectively, of the present measurements, represent a series of heat-flow values down the eastern flank of a part of the South American trench, with the last two measurements in the deepest part. Station 17 is just west of the western flank of the same trench. (3) There seems to be fair evidence for areas with low heat flow roughly paralleling, and to each side of, the high heat-flow band of the East Pacific Rise. To the west, the low heat-flow area is represented by stations 1, 2, 5, 6, 35, 36 and one of the previous Pacific measurements. To the east of the Rise, the evidence for a low is not as good, being represented only by station 26 and several of the previous Pacific measurements off the coast of Central America. The number of heat-flow measurements is not yet sufficient to establish how the trenches fit this general pattern ; but the rough parallelism of the Rise and trenches may suggest a relationship.

An interesting result of these measurements is the extreme range of the heat-flow values, which extend from a low of $0 \cdot 14 \times 10^{-6}$ cal./cm.^{2} sec. to a high of $8 \cdot 09 \times 10^{-6}$ cal./cm.^{2} sec., a ratio of more than 1 : 50. Even though the area studied has large topographic features, where differences of heat flow might be expected, the large magnitude of the range of heat flow is somewhat surprising. It is believed that some of the variation in heat flow may be due to irregularities in bottom topography, or to an irregular surface of rocks of good thermal conductivity buried by a smooth sediment surface, as suggested previously[1]. Although it is difficult to evaluate the combined magnitude of these effects, it appears that they would not alter the observed heat flow at any station from the assumption of heat flow through uniform, horizontal layers by more than a factor of two, and would not be systematically distributed. The measurements have not been corrected for these disturbances, but irregular bottom topography may have had some effect on stations 6, 10, 11, 15, 16, and 30.

Undoubtedly, most of the variations observed in oceanic heat flow are due to differences in flow of heat from the mantle of the Earth. The pattern of heat flow in the eastern Pacific, if verified by further measurements, is suggestive of a large convective cell in the upper mantle of the Earth. The rising part of the convection cell, bringing hot material near the surface, may be represented by the East Pacific Rise,

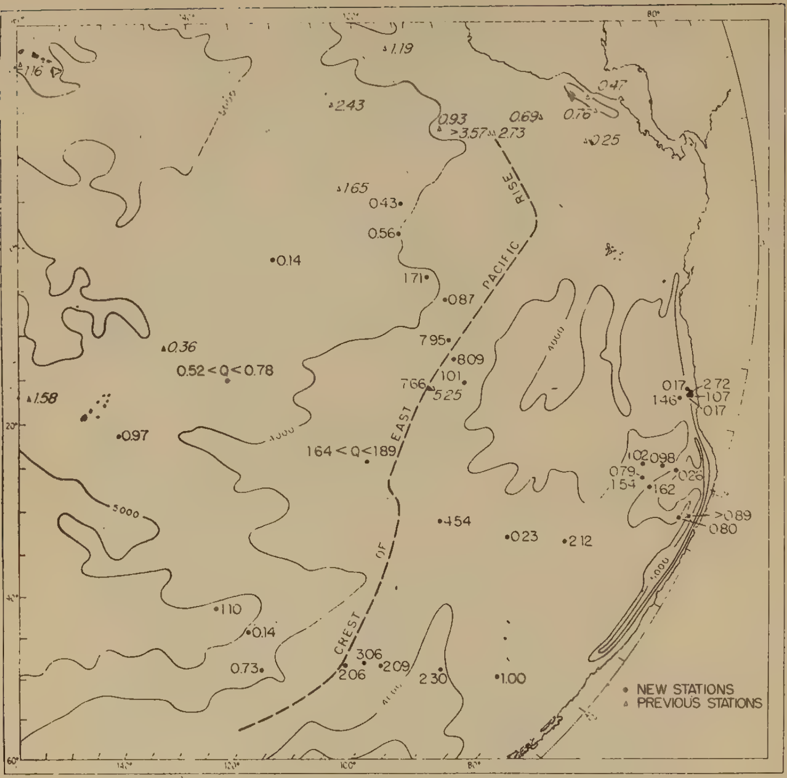
1.19
1.16
2.43
0.93
>3.57
2.73
0.69
0.76
0.47
0.25
1.65
0.43
0.56
0.14
1.71
0.87
EAST PACIFIC RISE
7.95
8.09
1.01
7.66
5.25
0.36
0.52 < Q < 0.78
1.58
0.97
164 < Q < 189
CREST OF EAST PACIFIC RISE
5000
4.54
0.23
2.12
0.17
2.72
1.46
1.07
0.17
1.02
0.98
0.79
1.54
0.26
1.62
>0.89
0.80
1.10
0.14
0.73
3.06
2.06
2.09
2.30
1.00
• NEW STATIONS
▵ PREVIOUS STATIONS
20°
40°
60°
140°
120°
100°
80°

Fig. 1

and the sinking parts by the possible low heat-flow areas on each side. Indeed, the lowest heat flows measured may be due entirely to the small amount of heat generated by radioactivity in the crust, with little or no heat coming from the mantle. The oceanic heat-flow values also show variations of relatively small horizontal extent not associated with topographic variations or with the large pattern, suggesting smaller-scale thermal anomalies in the mantle, perhaps also due to convection. A more closely spaced series of measurements in one of these areas is highly desirable.

Similar patterns may be expected for other areas of the Earth; high heat flow has been indicated also for the mid-Atlantic Ridge (Sir Edward Bullard, personal communication), a topographic feature of the Atlantic Basin similar to the East Pacific Rise. However, since convection could be driven by a deep distribution of radioactive heat sources under the ocean areas, it may be that similar patterns would not be observed in continental regions, where the radioactivity may be frozen uniformly in a relatively shallow crust. In fact, while the average heat flow seems to be about the same over continental and oceanic regions, the continental values show considerably less variation than the oceanic. However, this may result from a more limited distribution of continental heat-flow values; in fact, some areas of continents have been recently investigated which show unusually high heat flow[3,4]. Many problems have yet to be solved, and towards this end it is hoped that the results herein will be a stimulus for further measurements.

The measurements were made possible with the facilities of the Scripps Institution of Oceanography, and the interpretation of field observations was facilitated by a grant from the Institute of Geophysics, University of California. I wish to thank Prof. R. W. Raitt for encouraging the investigation and for many helpful discussions.

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Feb. 13.

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[1] Bullard, E. C., Maxwell, A. E., and Revelle, R., "Adv. in Geophys.", 3, 153 (1956).

[2] Revelle, R., and Maxwell, A. E., *Nature*, **170**, 199 (1952).

[3] Misener, A. D., *Trans. Amer. Geophys. Union*, **36**, 1055 (1955).

[4] Boldizsar, T., *Geofisica Pura e App.*, **29**, 120 (1958).

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Distribution and Differentiation of the North Pacific Myctophid Fish, *Tarletonbeania taylori*[1]

Robert L. Wisner

TARLETONBEANIA TAYLORI MEAD (1953) was described from six specimens collected near the northeastern shore of Honshu Island, Japan. It differs from its transpacific congener, *T. crenularis* (Jordan and Gilbert), the only other known species of the genus, primarily in that the caudal peduncle of the male bears an infracaudal as well as a supracaudal luminous gland. The females of both species bear neither gland.

During the latter part of 1953, when the Scripps Institution of Oceanography, with the support of the Office of Naval Research, conducted the Trans-Pacific Expedition across the northern Pacific and into the south-central part of Bering Sea, specimens of *T. taylori* were taken from the extreme northern areas of the Pacific but not from Bering Sea. The collections of *T. taylori* from the northeastern Pacific were later augmented by other agencies. I have studied the series of specimens now available from each area, with particular reference to meristic variation.

Acknowledgments

Grateful appreciation is extended to the several members of the Trans-Pacific Expedition for aid in the collection of specimens. In particular I thank Donald E. Powell, formerly Chief of the North Pacific Fisheries Exploration and Gear Research, Seattle, Washington, and Garth I. Murphy, Director of Pacific Oceanic Fisheries Investigations, Honolulu, Hawaii, both of the U.S. Fish and Wildlife Service, for making available specimens from the northeastern Pacific. Paratypes of *T. taylori*, USNM 164971 and 164972, were loaned by the United States National Museum through the kindness of Leonard P. Schultz, Curator of Fishes.

Methods

The vertebral centra were counted from X-ray plates. The hypural plate was included in the count. Fin rays were counted after the method of Hubbs and Lagler (1947). The photophore terminology follows that of Bolin (1939). The counts are combined for each area because few samples contained a sufficient number of specimens to provide statistical reliability.

Because the overlap between the two species in meristic counts is very considerable, precautions were taken to assure that the specimens without caudal luminous glands were assigned to the proper species. This was done by comparing the meristics of the group involved with data from specimens having caudal glands. In all samples except one, which is elaborated upon in the discussion, all evidence indicates that there was no mixture of species.

The meristic data are graphically analyzed following the method proposed by Hubbs and Hubbs (1953). In each bar the base line represents the extremes of range; the short, vertical line represents the mean value; the solid portion represents two standard errors of the mean plotted on each side of the mean; and the open, or outlined portion, one standard deviation plotted on each side of the mean.

Morphometric data disclosed little of value and are not given.

Geographical Variation of *Tarletonbeania taylori*

Within the range of *Tarletonbeania taylori*, as defined by the development of an infracaudal luminous gland, considerable difference is evident between the series from the northwestern and the northeastern Pacific in certain meristic characters, particularly in the number of vertebrae, in the total number of photophores in the anal series, and in the number of anal rays (Figs. 2–8). For both the posterior series (AOp) and the total anal photophores (AO) the data (Figs. 2 and 3, Table I) indicate the virtual certainty that the two areas do not comprise a homogeneous population. The indicated probability of significance is about $2.5 \times 10^8:1$. The data for the anterior anal series (AOa) in contrast, indicate about one chance in ten that the two groups are homogeneous (Fig. 4, Table I).

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[1] Contributions from the Scripps Institution of Oceanography, New Series. 1076

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The difference between means for vertebral centra (Fig. 5, Table II) is also of a high order of significance, the odds being slightly over 1.6 × 10^4:1 against the two populations being homogeneous.

The difference between means for numbers of gill rakers (Table IV) shows relatively little significance as compared to the previous meristic characters, the odds being 20 to 1 in favor of heterogeneity. The mean number of upper rakers for *T. taylori* from the northwestern Pacific is actually 5 rather than 6 as listed by Mead (1953). However, the total range of counts, as given by Mead, is confirmed.

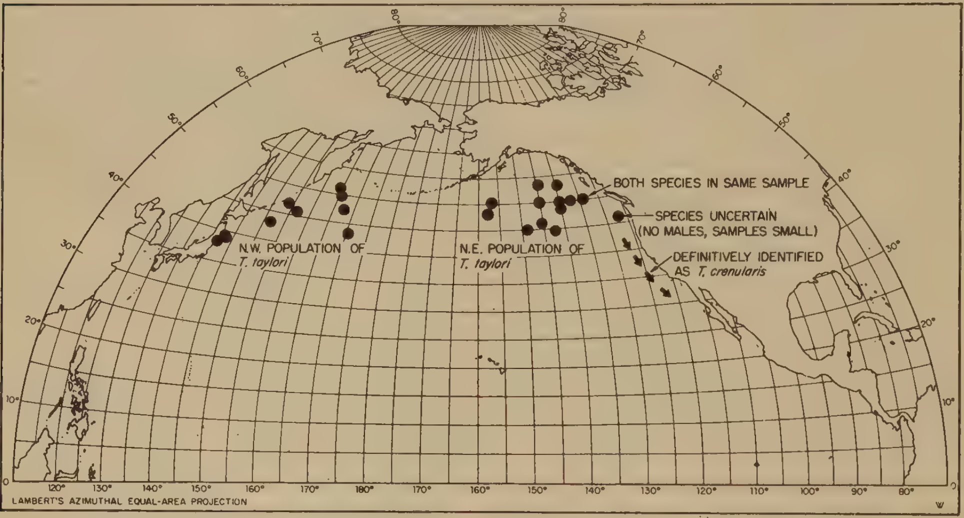

80°
70°
60°
50°
40°
30°
20°
10°
0
BOTH SPECIES IN SAME SAMPLE
SPECIES UNCERTAIN (NO MALES, SAMPLES SMALL)
DEFINITIVELY IDENTIFIED AS T. crenularis
N.W. POPULATION OF T. taylori
N.E. POPULATION OF T. taylori
120° 130° 140° 150° 160° 170° 180° 170° 160° 150° 140° 130° 120° 110° 100° 90° 80°
LAMBERT'S AZIMUTHAL EQUAL-AREA PROJECTION
W

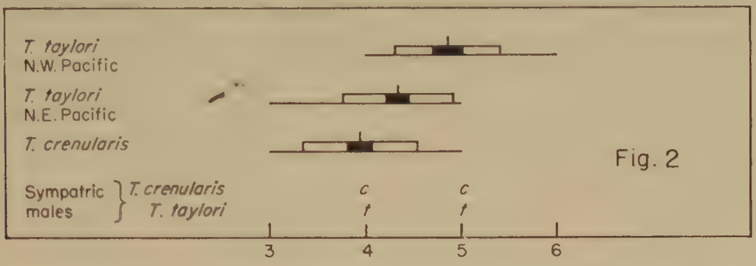
Fig. 1. Location of samples of *Tarletonbeania taylori* and *T. crenularis* studied.

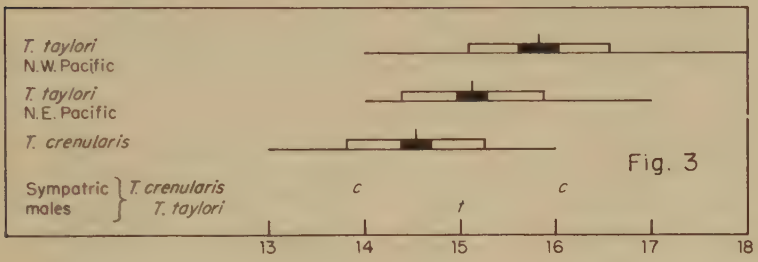
The differences between means for both the dorsal and pectoral fin rays (Figs. 6 and 7, Table III) indicate low levels of significance, the respective odds being 10 and 6 to one that the two populations are heterogeneous. However, the means for anal rays (Fig. 8, Table III) indicate odds of about 400 to 1 in favor of heterogeneity.

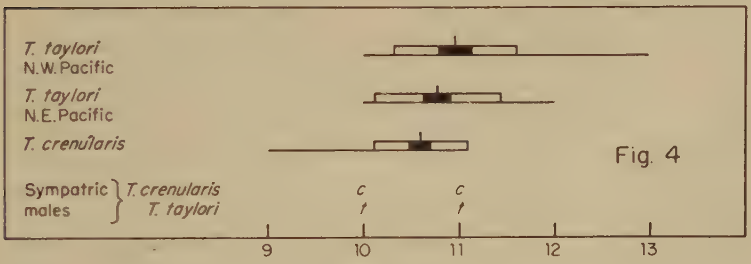
The degree of differentiation indicated for several characters and the apparent clines shown by Figures 2–8 involving *T. crenularis* and the two forms of *T. taylori* immediately suggest speciation at the subspecific level. However, the luminous-gland character, as indicated below, indicates specific separation. The test of Co-efficient of Difference, as described by Mayr, Linsley, and Usinger (1953), was applied to the two characters (total anal photophores and vertebrae) showing the most pronounced difference between the northwestern and northeastern populations of *T. taylori*. The results indicate that in regard to nonoverlap in characters too few individuals could be separated from each population to warrant subspecific separation. The same conclusion stems from a visual inspection of the graphs, according to the criteria presented by Hubbs and Hubbs (1953). However, in most meristic characters, the difference between the two forms of *T. taylori* equal or exceed those between the northwestern form of *taylori* and *T. crenularis* from off California, Oregon, and Washington.

All of the apparent clines tend in the same direction; the higher mean values for the northwestern form of *T. taylori* grade rather smoothly through means for the northeastern form into the means for *T. crenularis*. The obvious differentiation of the two forms of *T. taylori* and the apparent clinal relationship to *T. crenularis* suggests the possibility of hybridization.

However, all specimens of *T. crenularis* used in this study, plus many more not included in the statistical analyses, were examined for the simultaneous occurrence of both supracaudal and infracaudal luminous glands. No such occurrence was noted. Furthermore, there is a difference between the two species in the shape of the supracaudal gland. In no specimen of *T. crenularis* did the elongate, thin gland resemble the consistently much shorter and bulkier gland of *T. taylori*. A few males of *T. crenularis* bore a distinctive, pale, elongate area in the region normally occupied by the infracaudal gland of *T. taylori*, but this pale area on close inspection was seen to be caused merely by an absence, or a thinning, of melanophores. No trace of luminous tissue could be seen on gross examination.







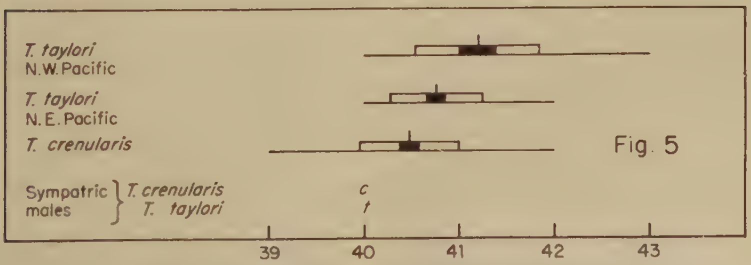


Fig. 2. Number of posterior anal organs (AOp).
Fig. 3. Number of total anal organs (AO).
Fig. 4. Number of anterior anal organs (AOa).
Fig. 5. Number of vertebral centra.

The consistent difference between the two species in the caudal glands does not in itself eliminate the possibility of hybridization. The presence or absence of the infracaudal gland, and the shape of the supracaudal gland, might be due to a single-factor Mendelian character. However, the distributional evidence indicates that *T. crenularis* does not commonly intermingle with *T. taylori*. The two were found together but once. Two males of each species were taken together at 50° 01′ N., Lat., 133° 58′ W. Long. (Fig. 1), along with ten females. In all meristic characters these females correspond with *T. taylori* rather than with *T. crenularis*. This may be an indication that *T. crenularis* seldom enters the area.

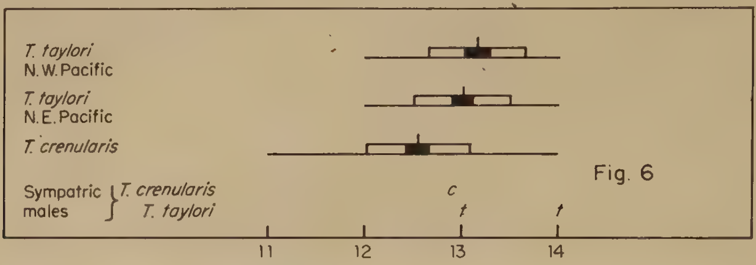


Fig. 6

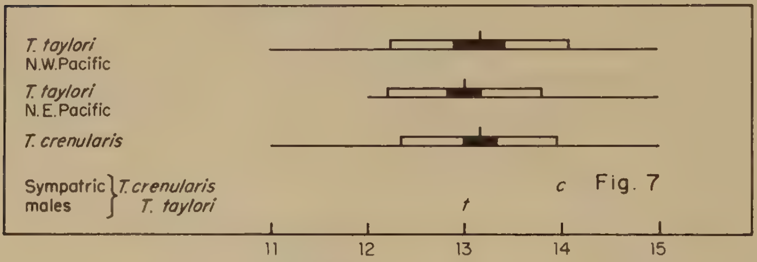


Fig. 7

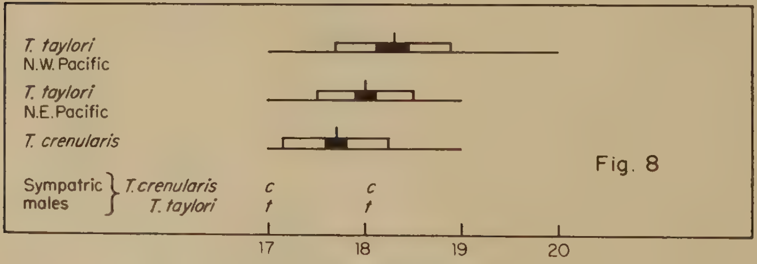


Fig. 8

Fig. 6. Number of dorsal fin rays.
Fig. 7. Number of left pectoral fin rays.
Fig. 8. Number of anal fin rays.

The counts of the two sympatric males of *T. crenularis* offer no conclusive evidence in regard to hybridization. As shown in Figures 2–8, one character may indicate a closer relationship to *T. crenularis* whereas another obviously favors *T. taylori*. Three characters show close relationship to *T. taylori* and three to *T. crenularis*. Two characters lie at the extremes of the range of each species. But one character, total AO, may be said to approach the mid-point expected to result from hybridization (Fig. 3). This is also true for the total count of the two males of *T. taylori*. All other counts, except those for dorsal and pectoral rays, are identical with those of the two males of *T. crenularis* (Figs. 2–8).

T. crenularis has been reported from the Gulf of Alaska, as follows: Bolin (1939) listed a specimen in the southern part of the Gulf, 49° N. Lat., 150° W. Long., but apparently the specimen was not examined by Bolin nor are any details given. Chapman (1940) listed a total of 18 specimens of *T. crenularis* ranging from near Kodiak Island, 57° 32′ N. Lat., 136° 25′ W. Long., across the Gulf to 55° 32′ N. Lat., 136° 25′ W. Long., and south to the Straits of Juan de Fuca. Almost all these locations lie within the range of *T. taylori* and there is little to indicate that the specimens could not represent the species. Chapman stated that "no supra- or infra-caudal luminous scales or patches are present in the specimens . . .". Because of the lack of caudal luminous scales in the females and young of both species, and the considerable overlap in ranges of meristic characters, it is not possible to state with certainty that specimens without caudal luminous scales, represent *T. crenularis*.

Table I

Frequency Distribution of the Anal Series of Photophores of *Tarletonbeania taylori* from the Northwest and Northeast Pacific Ocean, and of *T. crenularis* from off the Coast of California

AOa, Left

	9	10	11	12	13	N	Mean	$S(x-\bar{x})^2$	S.D.
T. taylori									
NW Pacific	..	11	34	7	1	53	10.96	21.92	.6431
NE Pacific	..	34	47	13	..	94	10.78	42.31	.6709
T. crenularis	2	33	56	..	..	91	10.59	25.96	.5341

AOp, Left

	3	4	5	6	N	Mean	$S(x-\bar{x})^2$	S.D.
T. taylori								
NW Pacific	..	11	38	4	53	4.87	14.08	.5508
NE Pacific	5	51	38	..	94	4.35	31.41	.5780
T. crenularis	19	58	14	..	91	3.95	32.73	.5997

Total AO, Left

	13	14	15	16	17	18	N	Mean	$S(x-\bar{x})^2$	S.D.
T. taylori										
NW Pacific	..	2	13	31	6	1	53	15.83	29.47	.7457
NE Pacific	..	18	49	24	3	..	94	15.13	52.47	.7471
T. crenularis	6	37	41	7	..	..	91	14.54	48.62	.7310

Table II

Frequency Distribution of Numbers of Vertebral Centra of *Tarletonbeania taylori* from the Northwest and Northeast Pacific Ocean and of *T. crenularis* from off the Coast of California

The hypural element is included

Vertebral Centra	39	40	41	42	43	N	Mean	$S(x-\bar{x})^2$	S.D.
T. taylori									
NW Pacific	..	5	26	12	1	44	41.20	19.16	.6599
NE Pacific	..	29	70	4	..	103	40.76	26.96	.4919
T. crenularis	1	60	56	1	..	118	40.48	33.47	.5928

If it is assumed that hybridization is not occurring and that *T. crenularis* may not be common in Gulf of Alaska waters, the immediate and obvious explanation of the pronounced differences between the northwestern and northeastern forms of *T. taylori* is that the two groups comprise distinct and self-sustaining populations. The very marked apparent clines that suggest intergradation with *T. crenularis* may be the fortuitous result of direct environmental influences or of convergent raciation.

Table III

Frequency Distribution of fin rays of *Tarletonbeania taylori* from the Northwest and Northeast Pacific Ocean, and of *T. crenularis* from off the Coast of California

Dorsal Rays

	11	12	13	14	N	Mean	$S(x-\bar{x})^2$	S.D.
T. taylori								
NW Pacific	..	3	38	12	53	13.17	13.47	.5042
NE Pacific	..	11	70	13	94	13.02	23.96	.5049
T. crenularis	1	38	49	1	89	12.56	25.91	.5395

Anal Rays

	17	18	19	20	N	Mean	$S(x-\bar{x})^2$	S.D.
T. taylori								
NW Pacific	2	35	14	2	53	18.30	19.17	.6014
NE Pacific	13	67	14	..	94	18.01	26.99	.5052
T. crenularis	31	55	5	..	91	17.71	28.57	.5604

Pectoral Rays

	11	12	13	14	15	N	Mean	$S(x-\bar{x})^2$	S.D.
T. taylori									
NW Pacific	1	13	19	16	4	53	13.17	47.47	.9464
NE Pacific	..	25	41	20	3	89	13.01	56.99	.8002
T. crenularis	1	17	42	28	3	91	13.16	58.53	.8020

In support of the idea of isolated, self-sustaining populations, as opposed to hybridization with *T. crenularis*, is the absence of any marked or consistent differences between the values of the standard deviations about the respective means (Table 1–3) such as would be expected if the northeastern stock of *T. taylori* has resulted from hybridization with *T. crenularis*. Only for the anal photophores do the values for the northeastern stock of *T. taylori* significantly exceed those for either the northwestern form of *T. taylori* or *T. crenularis.*

The circumstances suggest that the northeastern stock of *Tarletonbeania taylori* is largely distinct and self-sustaining, but some recruitment from the northwestern stock is possible. In fact, it is conceivable that the northeastern population arises directly from the northwestern, by reasons of environmental modification, over two or three generations, of individuals being carried eastward along the Aleutian or Subarctic current. The current structure favors this possibility. The Aleutian, or Subarctic, current dominates the north Pacific above about 42° N. Lat. (Sverdrup, Johnson and Fleming, 1942, p. 722) and culminates in the Alaska and California currents. As this current moves eastward it becomes warmed to the degree that it may be characterized as a warm current despite the fact that it carries subarctic water. As all record stations of *T. taylori,* except the few reported by Mead, are in an area extending approximately from 42° to 52° N. Lat., and from 45° to 53° N. Lat., in the northwestern and northeastern Pacific, respectively, they all lie within the influence of this current. Available information indicates this to be a rather slow current, probably not exceeding an average of about six miles per day. Thus it may well be that one or more spawnings occur during any migration, along with possible phenotypic changes engendered by the somewhat different environment.

TABLE IV

FREQUENCY DISTRIBUTION OF NUMBERS OF GILL RAKERS OF *Tarletonbeania taylori* FROM THE NORTHWEST AND NORTHEAST PACIFIC OCEAN, AND OF *T. crenularis* FROM OFF THE COAST OF CALIFORNIA

The central raker is included in "Total Rakers"

Upper Rakers*

	4	5	6	N	Mean	$S(x-\bar{x})^2$
T. taylori						
NW Pacific	2	45	4	51	5.04	5.92
NE Pacific	2	80	1	83	4.99	2.99
T. crenularis	1	86	4	91	5.03	4.90

Lower Rakers*

	9	10	11	N	Mean	$S(x-\bar{x})^2$
T. taylori						
NW Pacific	4	43	4	51	10.00	8.00
NE Pacific	23	58	2	83	9.75	19.69
T. crenularis	18	69	4	91	9.85	19.85

Total Rakers

	14	15	16	17	18	N	Mean	$S(x-\bar{x})^2$
T. taylori								
NW Pacific	..	6	38	6	1	51	16.04	15.92
NE Pacific	1	23	57	1	1	83	15.73	26.17
T. crenularis	..	19	65	6	1	91	15.88	27.67

* The counts for the upper and lower rakers do not include the central raker.

However, all available temperature and salinity data for the respective areas occupied by *T. taylori* indicate rather moderate differences in environment. Schott (1935, pl. 27) shows summer surface salinities for the habitats of *T. taylori* to range from 34.0 to 32.5 parts per thousand between the northwestern and northeastern habitats respectively. Temperatures from the surface to 400 meters depth are essentially the same, ranging from 10 to 15 C° at 200 meters and from 2 to 5 C° at 400 meters. Apparently, however, all temperatures average a few degrees colder for the northwestern area north of the influence of the Kuroshio current extension (Schott, *op. cit.* pls. 31, 32) (Sverdrup, *et al, op. cit.,* chart III).

Whereas the surface salinities and temperatures may appear to differ significantly over the north Pacific, it must be remembered that the myctophid fishes make extensive vertical migrations, certainly to a depth of at least 200 meters. It is very probable that greater extremes of temperature and salinity are encountered in such migrations than are likely to occur in the surface waters within the respective habitats. Therefore, it can not be stated with confidence that the small differences between the two habitats of *T. taylori* can alone be responsible for the observed changes in meristic characters. In fact it is hardly plausible to assume that differentiation within *T. taylori* is directly induced by the environment.

A causal mechanism responsible for the isolation of the two populations of *T. taylori* may well be the eastward drift in the North Pacific and the divergence of the Aleutian current into the Alaska and California currents along the North American coast. The Alaska branch forms a gyral which dominates the Gulf region southward to about 50° N. Most of the specimens of the northeastern form of *T. taylori* were taken along this latitude. Assuming the species to have originated in the northwestern Pacific, it is thus possible that the original migrants, upon reaching the Gulf of Alaska, remained under the influence of the gyral and did not return westward against the Aleutian current. The apparent failure to extend southward into United States waters, following the California current, may be due to a preference for the colder waters of the Gulf region, or possibly to inability to compete with the well-established *T. crenularis.*

It is concluded that the highly significant differences between the two segregated populations of *T. taylori* indicate that the northeastern form comprises an isolated population, chiefly confined to the Alaskan gyral, and largely uncontaminated by recruitment from the west or by hybridization with *T. crenularis* from the south.

LITERATURE CITED

BOLIN, ROLF L. 1939. A review of the myctophid fishes of the Pacific coast of the United States and of Lower California. Stanford *Ichthyological Bulletin*, 1: 101–5.

CHAPMAN, W. M. 1940. Oceanic fishes from the northeast Pacific ocean. *Occasional Papers of the British Columbia Provincial Museum*, (2): 14–16.

HUBBS, CARL L., AND HUBBS, CLARK 1953. An improved graphical analysis and comparison of samples. *Systematic Zoology*, 2(2): 49–57.

—— —— AND LAGLER, KARL F. 1947. Fishes of the Great Lakes region. *Bulletin Cranbrook Institute of Science*, 18: 9–10.

MAYR, E., LINSLEY, E. G., USINGER, R. L. 1953. Methods and Principles of Systematic Zoology, *McGraw-Hill Co., New York*, 146–7, table 12.

MEAD, Giles W. 1953. *Tarletonbeania taylori*, a new lanternfish from the western north Pacific. *Zoologica*, 38, part 2: 105–8.

SCHOTT, G. 1935. Geographie des Indischen und Stillen Ozeans, Verlag Von *C. Boysen, Hamburg*, pls. 27, 31, 32.

SVERDRUP, H., JOHNSON, M. W., Fleming, R. H. 1942. The Oceans. *Prentice-Hall, Inc., New York*, Chart III.

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Bacterial Populations in Sea Water as Determined by Different Methods of Enumeration[1]

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ABSTRACT

Five different cultural and two direct microscopic methods were employed for estimating the abundance of bacteria in samples of sea water collected from both oceanic and neritic areas. The cultural methods included macrocolony counts on nutrient agar, silica gel, and membrane filters, microcolony counts on membrane filters, and the extinction dilution method. Direct microscopic counts were made of microbes on membrane filters and of microbes transferred from membrane filters to glass slides. Direct counts showed the presence of from 13 to 9,700 times as many bacteria as cultural methods. The extinction dilution method and the microcolony membrane filter method gave counts 20 and 35 times higher, respectively, than did any of the macrocolony methods. Direct microscopic counts on membrane filters were approximately 150 times higher than plate counts, and the numbers of microbes transferred from membrane filters to glass slides were approximately 2,000 times higher than plate counts. In all of the cultural methods, a peptone-yeast extract medium was used.

Differences in the abundance of microorganisms obtained by the various methods are attributed to a variety of factors: the presence of bacteria in aggregates, selective effects of the media, and the presence of inactive cells. A marked decrease in bacterial numbers was observed just below the thermocline as reflected in the macrocolony methods but not by the direct microscopic methods. A considerable population of spirilli-like forms was noticed directly under the microscope but not after cultivation.

INTRODUCTION

Studies of microorganisms in natural waters involve enumeration as a general index of activity and as a measurement of biomass. Little has been done in evaluating the intrinsic significance of the results of counting methods. Although cultural methods of enumeration are widely used, they yield only a small percentage of the microorganisms actually present (ZoBell 1946). The application of direct microscopic methods in water bacteriology led to counts 200 to 5,000 times higher than plate counts (Butkevich 1932, 1938). Radsimovsky (1930) explained this difference in bacterial numbers by the presence of autotrophic and organophobic organisms. After comparing the bacterial numbers and the oxygen demand of corresponding water samples, Butkevich and Butkevich (1936) concluded that a considerable portion of the bacteria must be present in the resting stage. However, Alfimov (1954) doubted the occurrence of many "dead" bacteria in sea water and sediments. Thus, there exists uncertainty concerning the state of bacteria in natural waters as well as the value of the various methods used for enumeration.

In the present investigation, the abundance of microorganisms in oceanic and neritic areas of the Pacific Ocean was investigated by seven methods of enumeration.

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METHODS

Sampling locations

Stations where sea water samples were collected:

1) On October 31, 1957, sea water was ob-

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tained from an area approximately equidistant between Baja California and Guadalupe Island (29° 18′ N latitude; 116° 56′ W longitude) at depths of surface, 25, 50, 75, 100, and 200 meters.

2) On December 20, 1957, sea water was obtained from an area 16 miles off the coast of San Diego, California (32° 38′ N latitude; 117° 32′ W longitude), at depths of surface, 25, 50, 75, 100, and 200 meters.

3) On the following dates, surface sea water samples were collected off the Scripps Institution of Oceanography pier: January 3, 1958; January 17, 1958; and February 6, 1958 (a local tide pool was also sampled on this date).

Types of water samplers used:

1) Water samples obtained at sea for cultural methods of enumeration were collected in sterile J-Z bacteriological water samplers using collapsible rubber bottles (ZoBell 1946).
2) Water samples collected for direct methods were obtained in Van Dorn (1956) samplers.
3) Surface water samples obtained near shore were collected in sterile one-liter glass-stoppered bottles.

Media

Basal medium, 2216E (Oppenheimer and ZoBell 1952)—Bacto-peptone, 5 g; Bacto-yeast extract, 1 g; $FePO_4$, 0.01 g; Bacto-Agar used for pour plate method, 15 g; aged sea water (salinity adjusted to 28 g/L), 1,000 ml; pH adjusted to 7.6 to 7.8. Medium 2216, not containing yeast extract, was found superior to other media for development of maximum numbers of aerobic heterotrophic marine bacteria (ZoBell 1941). This medium was improved by the addition of yeast extract as confirmed by Carlucci and Pramer (1957). Two other media were also used in one experiment.

Succinate medium—Succinic acid, 2.0 g; NH_4NO_3, 1.0 g; K_2HPO_4, 0.1 g; aged sea water (salinity adjusted to 28 g/L), 1000.0 ml; pH adjusted with NaOH to 7.6 to 7.8.

Casein hydrolysate medium—Enzymatic casein hydrolysate (NBC), 1.0 g; NH_4NO_3, 1.0 g; K_2HPO_4, 0.1 g; aged sea water (salinity adjusted to 28 g/L), 1000.0 ml; pH adjusted to 7.6 to 7.8.

Methods of enumeration

Agar pour plate method—Samples of sea water estimated to produce between 20 and 500 colonies per plate were transferred aseptically to sterile (90-mm) plastic petri plates. In certain oceanic areas samples as large as 5 to 10 ml may be required. When working at sea the plates were supported by a weighted swinging table.

Sterile nutrient agar was transported in screw-cap prescription bottles and remelted at sea. Plates were poured with nutrient agar cooled to 40–45° C and mixed thoroughly with the sample. After solidifying on the swinging table, the plates were incubated for at least five days before counting colonies.

Extinction dilution method—Medium 2216E broth was prepared and sterilized in 9 ml amounts in test tubes. One ml portions of the water samples were inoculated into five replicates of the broth. Each of the replicates was diluted by 10-fold increments from 10^0 to 10^{-6} ml. Growth was determined by turbidity in the broth after incubation and the most probable number (MPN) of microorganisms estimated from the distribution of positive and negative tubes from the table of Hoskins (1934).

Silica gel method—The advantages of silica gel as a solidifying agent for microbiological media and some practical improvements in its preparation have been presented by Pramer (1957). In this investigation the method was modified for use with sea water.

The resin column and silica sol were prepared as described by Pramer (1957). The silicate source was $Na_2SiO_3 \cdot 9H_2O$ (3% SiO_2, w/v). The silica sol was sterilized by autoclaving at 10 lbs pressure for five minutes.

Three parts of the sterile silica sol were mixed with one part of sterile double-strength 2216E broth. Full strength aged sea water was employed as the liquid phase of the nutrient solution. This gave a final concentration of sea water of 25% (salinity of 8.5 g/L). Gelling time with this mixture was approximately six minutes. However, when triple strength artificial sea water (Lyman and Fleming 1940) was substituted for full strength aged sea water, the gel formed almost instantly. Careful adjustment of the pH to 7.5 to 7.8 with NaOH resulted in a firm silica gel.

Macrocolony membrane filter method—From 2 to 50 ml of sea water sample were passed through a sterile 47-mm type PH Millipore filter to concentrate the microorganisms. The filters were sterilized at 112°C for a few minutes and stored in sterile distilled water until used. The inoculated filters were placed on adsorbent cellulose pads soaked with 2216E nutrient solution in 60-mm petri plates. Three such plates were incubated in a 150-mm petri plate which served as a moist chamber. The time and temperature of incubation for each water sample are presented in tables of data. Macrocolonies are defined as those which are large enough to be visible to the naked eye. The filters were stained with Löffler's methylene blue in order to make very small colonies visible.

Microcolony membrane filter method—Employing methods described by Jannasch (1958), colonies developing on nutrient-impregnated membrane filters were counted under a microscope at a magnification of 430 to 970×. In the microcolony method a 25-mm Millipore filter was used to concentrate microbes in water samples, and only 1 per cent as much nutrient was added as in the macrocolony method. Decreased incubation times and low nutrient concentration avoid the possible toxicity of the latter and regulate overgrowth of rapidly growing cells.

Direct microscopic method on membrane filters—Water samples were treated with formaldehyde, and several dilutions of each sample were filtered to obtain optimal distribution of microorganisms on the filter surface (Beling 1950, Alfimov 1954, and Jannasch 1953, 1958). Sterile distilled water was added during the last stages of filtration to remove salts (Jerusalimsky 1932). Staining with methylene blue yielded better results in counting microcolonies, but a 1 per cent solution of erythrosine in 5 per cent phenol often proved superior for differentiating individual cells. Even with this staining technique, the low optical contrast of the microscopic fields occasionally made it difficult or impossible to differentiate small microbial forms from inorganic particles on the filter surface. Indistinct forms were not counted.

Mechanical cleaning of surfaces which come in contact with the water sample is required in direct methods rather than sterilization. Consequently, carefully cleaned and dried Van Dorn (1956) samplers were used for collecting large volumes of sea water for this direct method. The number of bacterial cells remaining on the inner surface of the samplers was estimated by examining the water used to rinse the samplers by the Cholodny method. The contamination was less than 0.1 per cent of the total cell count.

Cholodny method—The Cholodny (1928) method involves microscopic enumeration of microörganisms on glass slides after concentration by filtration. The Cholodny method was modified somewhat in the following experiments. Depending on the expected bacterial density, 100 to 2,000 ml of the sea water sample obtained with the Van Dorn (1956) sampler were fixed immediately with 1 per cent formaldehyde. The sample was passed through a membrane filter using the apparatus illustrated in Figure 1. By turning the two-way stopcock (E), the vacuum filtration was stopped when two to three ml were left above the filter. Salts were removed by washing several times with sterile distilled water. Care was taken to leave a few ml of solution above the filter. Two precautions in the design of the apparatus prevented deposits from sticking to the filter surface which would be difficult to remove quantitatively: (1) an ultrafine sinter-glass plate (B) with a lower filtration speed than the membrane filter and (2) a collodium loop (C) 2 mm wide, which was rotated mechanically on the filter surface during filtration (Bachman 1926). The numbers of microorganisms remaining on the membrane filters were determined by microscopic examination and served as a control. The bacterial cells remaining amounted to 1.5 per cent on the average and did not exceed 8.5 per cent of the total count. The concentrated sample was transferred quantita-

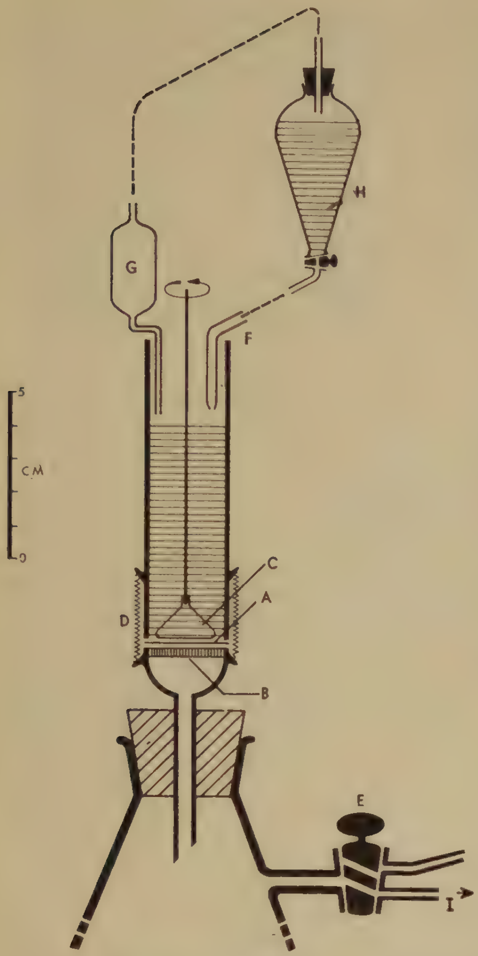


Fig. 1. Filtration apparatus for the Cholodny method. (A) membrane filter, (B) ultra-fine sinter glass plate, (C) stirring loop of collodium, (D) spring, (E) two-way stopcock, (F) sample entry, (G) level control, (H) separatory funnel (reduced in scale) containing sample, and (I) outlet connected to vacuum.

tively into small test tubes and adjusted to a certain volume (3 to 5 ml) with 5 per cent formaldehyde. Formaldehyde also was used to rinse the filter surface. With a calibrated capillary tube or micropipette, 0.01 ml of the concentrated sample was transferred to a slide, dried, and stained with a 2 per cent solution of erythrosine in 5 per cent phenol for at least five hours. The size of the dried area was measured with an ocular grid at an enlargement of 35 times. Possible contamination during 15 to 29 minutes of filtration was checked by examining filtered water. Bacterial cells introduced from the air did not influence the cell count. The per cent error of the counts obtained by this method is based on examination of 25 microscopic fields for each sample.

In the tables, per cent error is calculated by $S\bar{x}/\bar{x} \cdot 100$ where $\bar{x}$ is the mean and $S\bar{x}$ is the standard deviation of the mean.

RESULTS

The numbers of microorganisms detected by the various methods of enumeration from an oceanic area (Station 1) are presented in Table 1. The water temperatures at the various depths were recorded by a bathythermograph. The abundance of bacteria recovered from an area approaching the neritic zone (Station 2) are plotted in Figure 2. The number of bacteria recorded from the neritic waters off the Scripps Institution of Oceanography pier (Station 3) are presented in Table 2.

Evaluation of methods

As observed in Tables 1 and 2 as well as in Figure 2, the agreement among bacterial counts obtained by the agar pour plate method, silica gel method, and the macrocolonies on membrane filters was quite close. Submerged growth in the agar pour plate method which might tend to favor the development of anaerobic and microaerophilic microorganisms was no higher than that obtained by macrocolonies on membrane filters. In addition, no significant deviation was observed in samples from different depths of the sea. These results are not in agreement with those of Carlucci and Pramer (1957) who found as many as 30 to 40% more colonies arising after pouring plates than on surface-inoculated plates. These investigators have suggested the existence of a large percentage of microaerophilic and anaerobic bacteria in Atlantic ocean water.

ZoBell and Conn (1940) have shown that some marine bacteria are thermosensitive and are killed at the congealing temperature of agar. However, there is no direct evidence that the heat of the agar adversely affects the microorganisms developing on

TABLE 1. *Comparative numbers of microorganisms per ml indicated by different methods at Station 1*

Per cent error in parentheses. In all cultural methods the incubation temperature was 18 ± 1°C.

Depth m	Water temp. °C.	Plate[1] method		Serial dilution method (MPN)		Macrocolonies[1] on MF 5 Days	Microcolonies on MF 3 Days	Direct counts on MF
		5 Days	21 Days	5 Days	21 Days			
Surface	20.1	6 (10%)	11 (10%)	7	7	8 (9%)	68 (3.1%)	244 (1.8%)
25	20.1	14 (12%)	14 (12%)	5	5	14 (7%)	31 (5.4%)	262 (2.1%)
50	19.0	9 (19%)	10 (6%)	7	7	10 (12%)	30 (8.7%)	166 (6.4%)
75	15.0	1	2	0	0	6 (14%)	24 (11.2%)	147 (3.1%)
100	13.0	4 (14%)	6 (29%)	2	2	1 (15%)	29 (6.6%)	82 (11.3%)
200	10.0	3 (39%)	4 (58%)	2	2	5 (12%)	46 (4.0%)	179 (7.2%)

[1] An average of three replicates.

TABLE 2. *Comparative numbers of microorganisms per ml indicated by different methods of enumeration at Station 3*

Per cent error in parentheses. In all cultural methods the incubation temperature was 18 ± 1°C.

Area sampled	Water temp. °C.	Plate method		Silica gel method		Serial dilution method (MPN)		Macroc. on MF[4] 5 days	Microc. on MF 3 days	Direct count on MF	Cholodny method
		5 days	20 days	5 days	20 days	5 days	20 days				
Off pier	16.2	218[1] (8%)	239 (8%)	191[1] (7%)	218 (17%)	3500	3500	191 (11.2%)	1344 (6.2%)	1619 (7.4%)	25,800 (0.7%)
Off pier	16.0	37[2] (10%)	56 (11%)	17[1] (32%)	43 (14%)	220	350	61 (15%)	822 (9%)	1810 (5.3%)	41,100 (1.2%)
Off pier	15.9	25[3] (12%)	71 (5%)	—	—	64	1800	19 (13%)	108 (5.8%)	2290 (4.4%)	55,400 (3.2%)
Tide pool	16.2	75[3] (10%)	107 (9%)	—	—	700	9500	68 (17%)	136 (4.8%)	1780 (6.2%)	46,100 (2.2%)

[1] An average of 10 replicates.
[2] An average of 6 replicates.
[3] An average of 4 replicates.
[4] An average of 5 replicates.

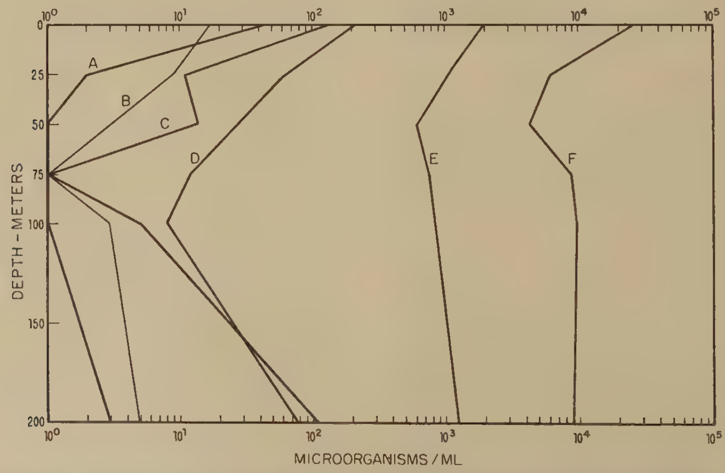


FIG. 2. Bacterial populations at depths obtained by different methods from Station 2. (A) agar pour plate method, (B) macrocolonies on membrane filters, (C) extinction dilution method, (D) microcolonies on membrane filters, (E) direct count on membrane filters, and (F) Cholodny method.

TABLE 3. *Number of microcolonies per ml as influenced by nutrients, period of incubation, and concentration of the water samples from Station 1*

Medium	Peptone-yeast extract (diluted 1:100)									Succinate (diluted 1:100)									Casein hydrolysate (diluted 1:100)								
Amount of water filtered...	2 ml			4 ml			8 ml			2 ml			4 ml			8 ml			2 ml			4 ml			8 ml		
Period of incubation (18 ± 1° C) hr	24	48	72	24	48	72	24	48	72	24	48	72	24	48	72	24	48	72	24	48	72	24	48	72	24	48	72
Depth, meters																											
Surface.........	22	59	**68**	29	52	—	34	—	—	11	14	17	9	17	**31**	16	29	22*	22	25	34	19	41	—	16	**53**	—
25.............	20	23	31	28	**55**	—	48	54	—	12	14	20	16	17	**26**	19	21	24	21	24	36	16	28	31	24	**39**	—
50.............	14	25	30	16	36	**52**	21	44	—	0	4	7	4	13	14	7	10	**18**	0	11	29	8	19	28	6	23	**44**
75.............	6	23	24	8	37	**46**	10	36	—	0	3	9	4	5	11	6	**19**	10*	0	0	14	1	6	9	6	8	**15**
100.............	0	13	29	6	21	30	6	27	**36**	0	8	14	0	12	18	13	17	**22**	0	4	13	0	16	21	5	**26**	20*
200.............	15	27	**46**	22	39	—	23	38	—	8	14	22	2	10	**26**	4	16	19	8	12	31	6	18	26	13	**42**	—

— = overgrowth of membrane filters
* = decrease in the number of colonies due to overgrowth
Bold face type = maximum number of microcolonies per depth and medium used

TABLE 4. *Ratio of microbial counts, range of values, and per cent error of five different methods compared to plate counts computed from all data*

	Plate method	Macrocolonies on MF	Serial dilution method	Microcolonies on MF	Direct counts on MF	Cholodny method
Mean	1	1.16	21.8	32.1	147	2100
Range	—	0.2–4.0	0.3–35	1.6–34	13–840	108–9700
Per cent error	—	17.1	19.2	12.7	8.5	20.7

agar plates as compared to those on membrane filters or silica gel.

Bacterial counts from agar pour plates were higher than those from silica gel plates (Table 2). This was true at sea as well as in near-shore samples. This effect may be attributed to specific salt requirements of marine bacteria (ZoBell 1941). In addition, the composition of unwashed agar is variable (Yaphe 1957), and micronutrients in the agar might be expected to stimulate marine bacteria (MacLeod *et al.* 1954, Jones 1957). ZoBell (1941) found about three to four per cent of the bacteria in the sea digest agar.

The most probable number (MPN) of microorganisms determined by the extinction dilution method was considerably higher than the macroscopic colony count, although the nutrient solution used in this method was identical with that used in the other cultural methods (Fig. 2 and Tables 2 and 4). This condition was not evident in oceanic water samples (Table 1). The increased counts in the majority of samples due to the liquid medium are attributed to the dispersion of bacterial aggregates and clumps on detritus as regulated by the surface tension depression of the medium. La Riviere (1955) has demonstrated that 1% peptone drops the surface tension of water by 18 dynes/cm, and 1% yeast extract by 25 dynes/cm. Surface tension depressions approaching this order of magnitude would be sufficient to disrupt bacterial aggregates causing the observed increase in the final count (Jones and Jannasch 1959). These results agree with those of Butkevich (1932) who obtained from ten to a hundred times as many bacteria by extinction dilution as by plate counts, using water samples from the Barents Sea. Butterfield (1933) reported good agreement between plate counts and the MPN of extinction dilution employing 50 replicates for the plates and 50 of each of three dilutions using *Escherichia coli*. He found 37% higher values by extinction dilution using the same experimental design when *Aerobacter aerogenes* was used as the test organism. The difference between the bacterial numbers obtained using the two test bacteria was ascribed to the greater tendency for the *Aerobacter aerogenes* cells to clump due to the presence of mucoid substances.

In the microcolony technique on membrane filters three small petri dishes were

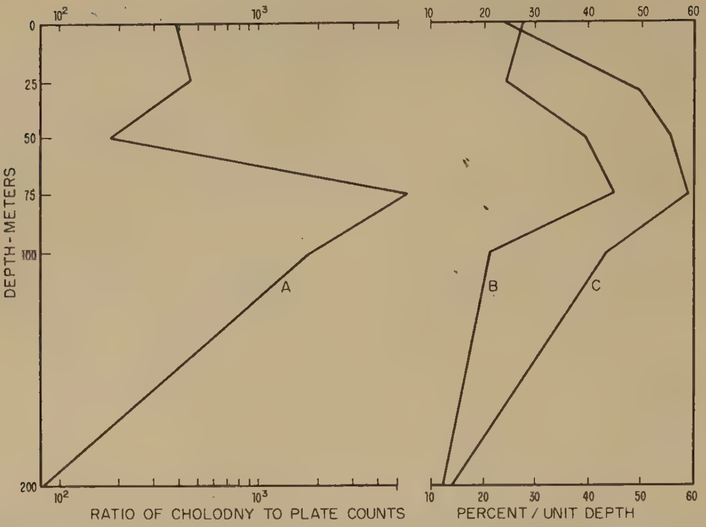


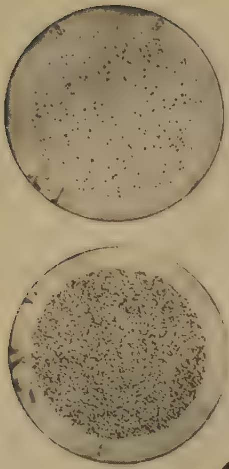
FIG. 3. Variations with the vertical distribution of microbial populations at Station 2. (A) ratio of microorganisms/ml obtained by the Cholodny method to microorganisms/ml recorded by agar pour plate method, (B) per cent of spirilli-like organisms per unit depth as determinated from the Cholodny count, and (C) per cent of aggregated microorganisms per unit depth as determined by Cholodny method.

placed in a larger one which served as a moisture chamber during incubation. Each of the small petri dishes contained three membrane filters which were divided, again, in three parts before incubation. In this way, three combinations of three different factors (nutrients, time of incubation, and concentration of sample) were compared, and 27 different values were obtained for each of the samples tested (Table 3).

The bacterial numbers obtained by the microcolony method demonstrate dependence on the incubation time. After 24 hours, groups of 2 to 20 cells developed on the membrane filter surface (Figs. 5 and 6). Single cells, presumably inactive, were not counted. Often colonies appear to have spread (Fig. 5). After approximately 48 hours in these experiments, colonies were composed of several hundred cells (Figs. 7 and 8). In many cases, colonies had begun to merge in 72 hours. Therefore, the colony counts may decrease before the membrane filter has been overgrown completely (Table 3). Sometimes dense colony centers indicate the existence of several original loci (Fig. 9).

Deviations from this general pattern of development are caused by density of bacteria on the filter surface (Table 3). In general, maximum counts appeared earlier when larger amounts of sample were used. Due to the density of bacteria in the water sample the maximum count occurred at a characteristic place in the series of nine experiments. Only the counts in the same columns are comparable. Of the three media tested, the peptone-yeast extract medium proved superior as indicated by the development of more colonies in a short period of time with early overgrowth of the filters. Similar growth ratios for these nutrients were obtained by the agar pour plate method using the same water samples. Generally, higher counts obtained by this method may result from the low nutrient level. In only a few cases were macrocolonies apparent on these filters after several weeks of incubation. Comparing the photomicrographs of Frost (1921) taken from microcolonies on the surface of agar plates with the type of growth on membrane filters, no considerable difference was noticed (Fig. 10).

Direct microscopic examination of membrane filters yielded lower numbers than



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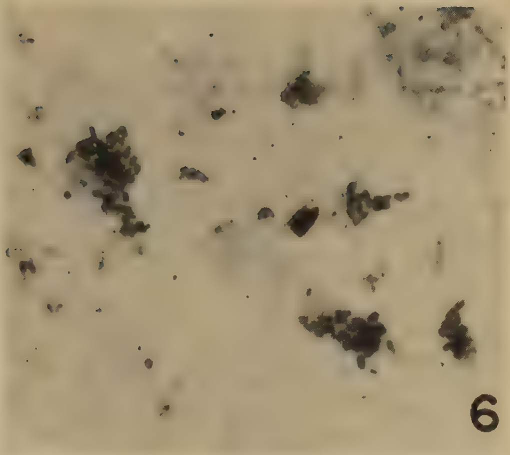

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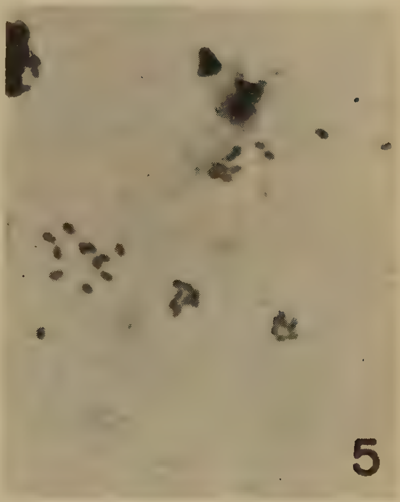

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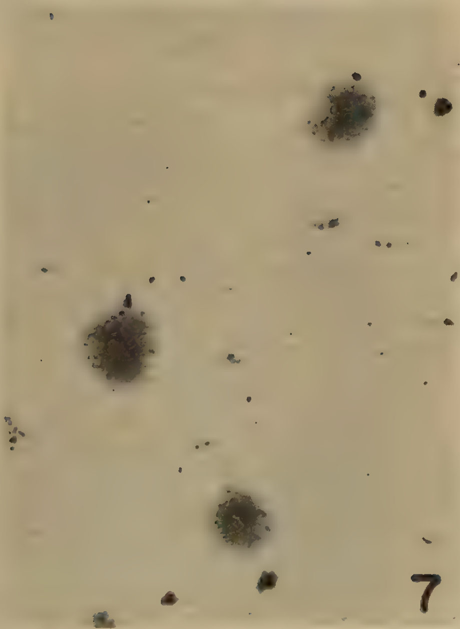

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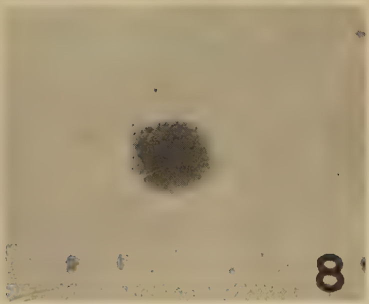

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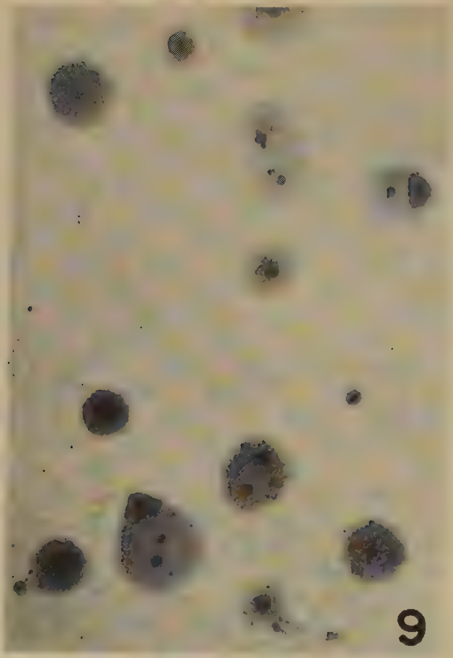
Fig. 4. Macrocolonies on membrane filters stained with Löffler's methylene blue stain.

Figs. 5 and 6. Microcolonies on 2216E medium (diluted 1:100) after 24 hours incubation at 18 ± 1°C on membrane filters. Magnification 970×.

Figs. 7 and 8. Colonies on 2216E medium (diluted 1:100) after 48 hours incubation at 18 ± 1°C on membrane filters. Magnification 500× and 700×, resp.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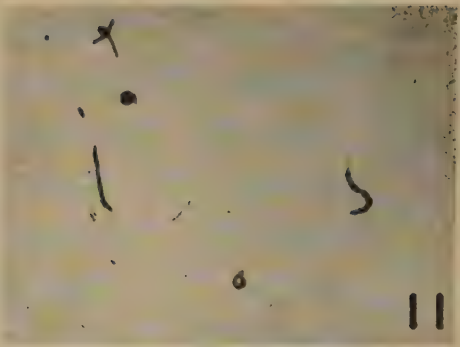
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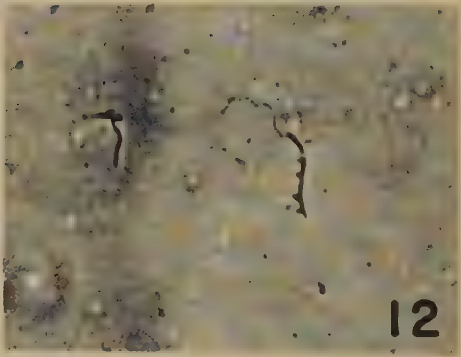
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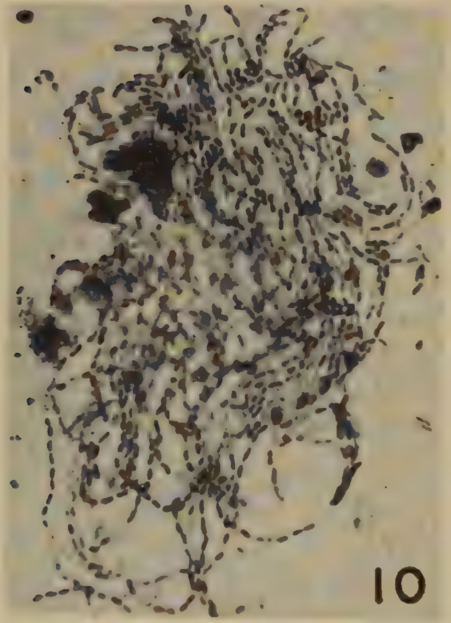
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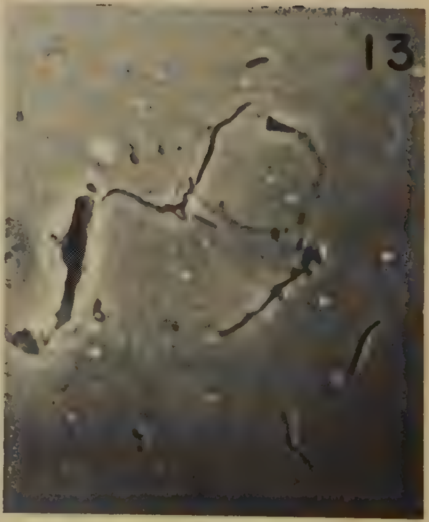
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FIG. 9. Colonies on casein hydrolysate medium (diluted 1:100) which have grown together after 72-hours incubation at 18 ± 1°C on membrane filters. Magnification 150×.

FIG. 10. Typical colony of a chain forming organism on membrane filter. Magnification 900×.

FIGS. 11–13. Spirilli-like and filamentous microorganisms stained with erythrosine obtained by the Cholodny method from samples of 75 and 200 meters, respectively, at Station 2. Magnification 1500×. Figures 12 and 13 reproduced from phase contrast.

those obtained by the Cholodny method (Table 4). Small and weakly stained cells may escape observation on the membrane filters due to the lower optical contrast of the preparation. The Cholodny method has been improved by the use of membrane filters of smaller porosity than those of Cholodny (1928, 1929) and Novobrantzev (1932), 0.3 μ as compared with 2.0 μ.

Evaluation of the vertical distribution of marine bacteria

As indicated in Table 1 and Figure 2, the results obtained by the various methods at depths down to 200 meters indicated a similar distribution of microorganisms in both vertical casts. The largest counts of bacteria occurred in surface waters, decreasing down to 75 meters, with an increase in abundance at 200 meters. Similar vertical distributions of microorganisms in the sea have been observed by Kriss and Rukina (1952), who demonstrated minimum bacterial counts at depths of 25 to 100 meters. This minimum corresponds roughly to the location of the thermocline.

A marked deviation of the ratio between direct microscopic counts and cultural method counts was observed at the various depths. The ratio of microorganisms obtained by the Cholodny method compared to the plate method at Station 2 are plotted at the various depths in Figure 3. These results indicate very few colonies developing on agar plates as opposed to relatively large numbers of cells observed directly, especially at 75 and 100 meters.

With both of the direct methods large spirilli-like organisms (4–15 μ long, 1–3 μ wide), as shown in Figures 11–13, were observed throughout the vertical casts. The long flagella (5–20 μ) were stained by erythrosine. Some of these organisms were motile in wet mounts prepared from water samples concentrated by filtration. The vertical distribution of these microorganisms in per cent of the Cholodny count is shown in Figure 3. None of these forms were observed in microscopic preparations made from colonies or dilution tubes, developing from the same water samples.

The percentage of microbes at various depths attached to detritus or observed in clumps as determined by the Cholodny method are plotted in Figure 3. The curve indicates less clumping where the plate count figures were highest (surface and 200 meters). In addition, the per cent errors of the direct counting methods (Table 1) show the lowest values in the same samples. The highest errors appear in samples of 75 and 100 meters.

DISCUSSION

Agar still appears to be the best solidifying agent for enumeration of bacteria at sea. However, silica gel has certain advantages for studying the nutritional requirements of bacteria, because it is a chemically defined substance and biologically inert. In addition, silica gel solidifies at any desired temperature within the biological range. Both of these solidifying agents are superior to gelatin, because many marine bacteria liquefy gelatin, which results in the merging of colonies before slow-growing bacteria have had time to develop visible colonies (ZoBell 1941).

Direct microscopic methods possess the advantages of revealing a more exact enumeration of the microorganisms in a sample than cultural methods regardless of their growth requirements or their physiological condition, and these results can be obtained in a very short period of time. However, there is no way to determine whether the bacteria observed are living or dead, and they cannot be used for cultural studies. Direct counts may be increased by the presence of non-proliferating, inactive, or dead cells. Karsinkin and Kusnetsov (1931) and Alfimov (1954), using erythrosine stain to differentiate living from dead protoplasm, found low percentages of dead bacteria in lake and sea water. Kusnetsov (1958) reported that dead bacteria constitute about 10 per cent of the total number of bacteria in lake water as determined by Peshkov's staining method. Strugger (1949), using acridine orange, obtained similar results in soil.

Direct microscopic methods are complicated by particulate matter in the sample simulating the appearance of microorganisms. Clumps are difficult to count. Therefore, no organism was counted unless it could be distinguished clearly from detritus. Cocciform bacteria were counted only when clearly differentiated. Due to these precautions, the actual bacterial counts are probably higher than those reported for the direct microscopic methods. The staining reaction of erythrosine was not used to distinguish between organic and inorganic material or living and dead protoplasm as suggested by Karsinkin and Kusnetsov (1931).

Ratios comparing the results obtained by cultural and direct microscopic methods for all of our experiments are presented in Table 4. The range of comparable ratios in lake water determined by Kusnetsov and Karsinkin (1931) using an evaporation technique for concentrating the sample for microscopic examination was 1:2,000–4,000. Unfortunately, this method is not applicable for sea water samples. Collins and Kipling (1957) obtained from 6 to 11,000 times as many bacteria by their direct method as by plate counts from Lake Windemere North Basin water. Salimovskaya-Rodina (1938) found up to 5,000 times higher counts in lake water by direct microscopic methods than by plate counts. According to Butkevich (1938), these ratios increase with the decrease of organic matter in the water.

Bacterial populations were reported to be directly proportional to organic matter by Novobrantzev (1932) and Chartulari and Kusnetsov (1937). According to Kriss (1953), at depths descending from the thermocline the bacterial numbers are regulated by the concentration of organic matter. As suggested by Butkevich (1938), the the converse of curve A in Figure 3 may present a rough index of the relative distribution of organic matter with depth. In this respect, it is noteworthy that our highest numbers of microorganisms were at the surface in Pacific Ocean water as were those of Lloyd (1930) in the Clyde Sea. Another possible explanation for the deviation of the ratio between direct microscopic and cultural counts at various depths is the different nutritional requirements of the populations at these depths. The spirilli-like organism is an example of a microorganism which escapes detection by cultural techniques. It is probable that other marine bacteria in these samples also did not develop into colonies with the nutrients used.

Another factor which decreases the plate counts is aggregation of bacteria as indicated by the direct methods. According to Jennison (1937) and Ziegler and Halverson (1935), the occurrence of clumps of bacteria is the main reason for the differences between direct microscopic and cultural counts of cells in cultures. A detailed study of the existence of microbial aggregates in the sea will appear shortly (Jones and Jannasch 1959).

REFERENCES

ALFIMOV, N. M. 1954. Comparative evaluation of methods for the determination of bacterial counts in sea water. Microbiology (Moscow), **23:** 693. (Russian).

BACHMANN, H. 1926. Der Mikrofiltrierapparat von Gimesi. Z. Hydrol., **11:** 271–276.

BELING, A. 1950. Bakteriologische Untersuchungen während der Fulda-Expedition 1948. Ber. Limnol. Flussstat. Freudenthal, **2:** 4–10.

BUTKEVICH, V. S. 1932. Zur Methodik der bakteriologischen Meeresuntersuchungen und einige Angaben über die Verteilung der Bakterien im Wasser und in den Böden des Barents Meeres. Trans. Oceanogr. Inst. Moscow, **2:** 5–39. (Russian, German summary).

———. 1938. On the bacterial populations of the Caspian and Azov Seas. Microbiology (Moscow), **7:** 1005–1021. (Russian, English summary).

BUTKEVICH, N. V., AND V. S. BUTKEVICH. 1936. Multiplication of sea bacteria depending on the composition of the medium and on temperature. Microbiology (Moscow), **5:** 322–343. (Russian, English summary).

BUTTERFIELD, C. T. 1933. Comparison of the enumeration of bacteria by means of solid and liquid media. U. S. Public Health Repts., **48** (42): 1292–1297.

CARLUCCI, A. F., AND D. PRAMER. 1957. Factors influencing the plate method for determining abundance of bacteria in sea water. Proc. Soc. Expt. Biol. Med., **96:** 392–394.

CHARTULARI, E. M., AND S. J. KUSNETSOV. 1937. Die Ergebnisse der Gesamtzählung der Bakterien im Wasser einer Reihe von Seen des Wyschne-Volotzkij Rayons. Arb. Limnol. Sta. Kossino, **21:** 117–124. (Russian, German summary).

CHOLODNY, N. 1928. Contributions to the quantitative analysis of bacterial plankton. Trav. Sta. Biol. Dniepre, **3:** 157–171. (Russian, English summary).

(156)

——— 1929. Zur Methode der quantitativen Erforschung des bakteriellen Planktons. Zbl. Bakt., Abt. 2, **77**: 179–193.

Collins, V. G., and C. Kipling. 1957. The enumeration of waterborne bacteria by a new direct count method. J. Appl. Bacteriol., **20**: 257–264.

Frost, W. D. 1921. Improved technique for the micro- or little-plate method of counting bacteria in milk. J. Infectious Diseases, **28**: 176–184.

Hoskins, J. K. 1934. Most probable numbers for evaluation of Coli-aerogenes tests by fermentation tube method. U.S. Public Health Repts., **49**: 393–405.

Jannasch, H. W. 1953. Zur Methode der quantitativen Untersuchung von Bakterienkulturen in flüssigen Medien. Arch. Mikrobiol., **18**: 425–430.

———. 1958. Studies on planktonic bacteria by means of a direct membrane filter method. J. Gen. Microbiol., **18**: 609–620.

Jennison, M. W. 1937. Relations between plate count and direct microscopic count of *E. coli* during the logarithmic growth period. J. Bacteriol., **33**: 461–477.

Jerusalimsky, N. D. 1932. Ein Versuch die Bakterienpopulation des Moskauflusses und seiner Zuflüsse nach der direkten Methode der Bakterioskopie zu untersuchen. Microbiology (Moscow), **1**: 147–175. (Russian, German summary).

Jones, G. E. 1957. The effects of organic metabolites on the development of marine bacteria. Bacteriol. Proc., pp. 16–17.

Jones, G. E., and H. W. Jannasch. 1959. Aggregates of bacteria in sea water as determined by treatment with surface active agents. Limnol. Oceanogr. (In press).

Karsinkin, G. S., and S. J. Kusnetsov. 1931. Neue Methoden in der Limnologie. Arb. Limnol. Sta. Kossino, **13**: 47–68. (Russian, German summary).

Kriss, A. E., and E. A. Rukina. 1952. Biomass of microorganisms and their rates of reproduction in oceanic depths. Zhur. Obsc. Biol., **13**: 346–362. (Russian).

——, 1953. Microorganisms and biological productivity of natural waters. Perioda (Leningrad), **5**: 49–59. (Russian).

Kusnetsov, S. J. 1958. A study of the size of bacterial populations and of organic matter formation due to photo- and chemosynthesis in water bodies of different types. Verh. Internat. Ver. Limnol., **13**: 156–169.

Kusnetsov, S. J. and G. S. Karsinkin. 1931. Direct method for the quantitative study of bacteria in water and some considerations on the causes which produce a zone of oxygen-minimum. Zbl. Bakt., Abt. 2, **83**: 169–179.

La Rivière, J. W. M. 1955. The production of surface active compounds by microorganisms and its possible significance in oil recovery. I. Some general observations on the change of surface tension in microbial cultures. Antonie Van Leeuwenhoek, **21**: 1–8.

Lloyd, B. 1930. Bacteria of the Clyde Sea area: a quantitative investigation. J. Mar. Biol. Assoc., U. K., **16**: 879–908.

Lyman, J., and R. H. Fleming. 1940. Composition of sea water. J. Mar. Res., **3**: 134–146.

MacLeod, R. A., E. Onofrey, and M. E. Norris. 1954. Nutrition and metabolism of marine bacteria. I. Survey of nutritional requirements. J. Bacteriol., **68**: 680–686.

Novobrantzev, P. V. 1932. The development of bacteria in lakes depending on the presence of easily assimilable organic matter. Microbiology (Moscow), **6**: 28–36. (Russian, English summary).

Oppenheimer, C. H., and C. E. ZoBell. 1952. The growth and viability of sixty-three species of marine bacteria as influenced by hydrostatic pressure. J. Mar. Res., **11**: 10–18.

Pramer, D. 1957. The influence of physical and chemical factors on the preparation of silica gel media. Appl. Microbiol., **5**: 392–395.

Radsimovsky, R. 1930. Vorläufige Angaben über die Dichtigkeit der bakteriellen Besiedlung einiger Gewässer. Trav. Sta. Biol. Dniepre, **5**: 385–402. (Russian, German summary).

Salimovskaja-Rodina, A. G. 1938. Concerning the vertical distribution of bacteria in the waters of lakes. Microbiology (Moscow), **7**: 789–803. (Russian, English summary).

Strugger, S. 1949. Fluoreszensmikroskopie und Mikrobiologie. Hannover, M. V. H. Schaper. pp. 151–173.

Van Dorn, W. G. 1956. Large volume water samplers. Trans. Am. Geophys. Union, **37**: 682–684.

Yaphe, W. 1957. The use of agarase from *Pseudomonas atlantica* in the identification of agar on marine algae (Rhodophyceae). Can. J. Microbiol., **3**: 987–994.

Ziegler, N. R., and H. O. Halvorson. 1935. Application of statistics to problems in bacteriology. IV. Experimental comparison of the dilution method, the plate count and the direct count for the determination of bacterial populations. J. Bacteriol., **29**: 609–634.

ZoBell, C. E. 1941. Studies on marine bacteria. I. The cultural requirements of heterotrophic aerobes. J. Mar. Res., **4**: 42–75.

———. 1946. Marine microbiology: a monograph on hydrobacteriology. Chronica Botanica Co., Waltham, Mass. pp. 41–58.

ZoBell, C. E., and J. E. Conn. 1940. Studies on the thermal sensitivity of marine bacteria. J. Bacteriol., **40**: 223–238.

Deep-Sea Research, 1959, Vol. 5, pp. 283 to 289. Pergamon Press Ltd., London. Printed in Great Britain

Reflexion studies in the eastern equatorial Pacific

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(*Received* 28 *October* 1958)

Abstract—A limited seismic reflexion survey has been made in a portion of the equatorial Pacific far from land and shielded from turbidity-current deposition. It covers the boundary between present-day clay deposition in the north and present-day carbonate deposition in the south. The profiles show that the sediment is decidedly thicker in the carbonate area and provide evidence for a greater rate of accumulation in valleys than on hills.

INTRODUCTION

In November 1954, the research vessel *Spencer F. Baird* occupied a series of closely spaced coring stations in the area near 125°W, 3½° to 13½°N. While the coring was being done, reflexion shots were fired whenever they would not interfere with other operations. The results of this admittedly limited survey are presented here, together with a few tentative conclusions about marine sedimentation derived therefrom.

This is an area of low hills, approximately 4500 m below sea level, with a few small seamounts. It lies along the boundary of clay and calcium carbonate deposition (see Fig. 1) and is remote from land sediment sources. It has been referred to as the " Eupelagic Area " by Arrhenius (1952) who has suggested that this area is probably one of purely pelagic sedimentation free of turbidity-current deposition from land sources. He has reported high rates of sedimentation in the carbonate zone. A determination of variation of sediment thickness across the border of the calcareous area may serve to tell whether this local high rate of deposition has existed in the past.

The Clipperton Fracture Zone crosses the area, possibly coincidentally, at the northern margin of the calcareous area. The average sea-depth changes across the fracture zone and is about 200 m shoaler on the south side. Detailed bathymetry is given by Menard and Fisher (1958).

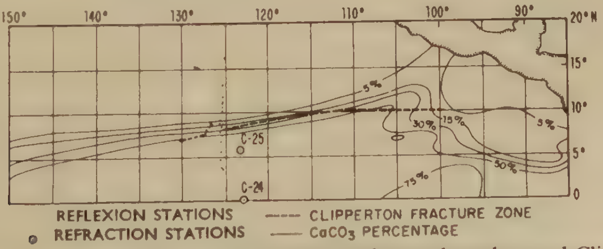

Fig. 1. Location of stations with respect to calcium carbonate boundary and Clipperton Fracture Zone. Modified from Arrhenius (1952).

FIELD PROCEDURE

The locations of the reflexion shots were controlled by the needs of the coring programme. Locations were along two generally north-south lines about 200 km apart (Fig.1) with close spacing on either side of the carbonate boundary and wider

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spacing farther away. In a few locations a detailed bathymetric survey was made to establish a base map, and attempts were made to place cores and shots specifically over hilltops and valley floors. Two or more reflexion shots were fired on each station.

Shots were half-pound tetryl blocks, fired with time fuses at a depth of about 45 m. From one to four hydrophones were streamed at depths between 30 and 60 m. Sub-bottom reflexions were distinguished from side echoes by recording on multiple frequency bands and picking only those low-frequency arrivals which were unaccompanied by high-frequency returns.

SEISMIC RESULTS

A sample record is shown in Fig. 2. In this record, the first to fourth multiple reflexions from the basement were received; they are indicated by the events marked B_1, B_2, B_3, and B_4. The events marked S_1, S_2, S_3, and S_4 are the reflexions from the upper surface of the sediment. They are distinguishable only for the first two multiples on the high-frequency traces; the travel times for the third and fourth arrivals were computed. These sub-bottom reflexions correspond to type " N " reflexions of Hersey and Ewing (1949) as do most of the records obtained in this area. A few type

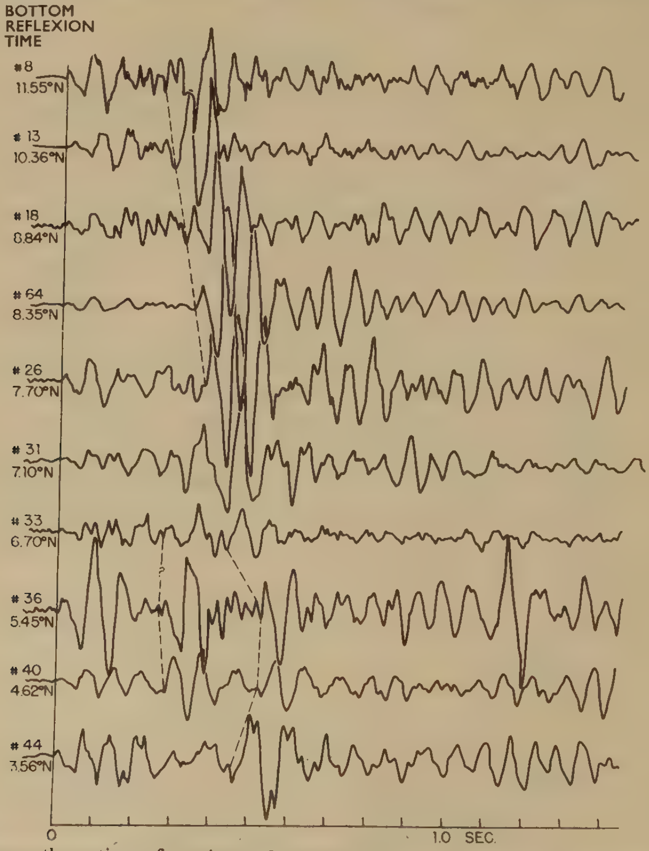

Fig. 3. North-south section of tracings of selected records. Alignment is on time of the first bottom reflexion.

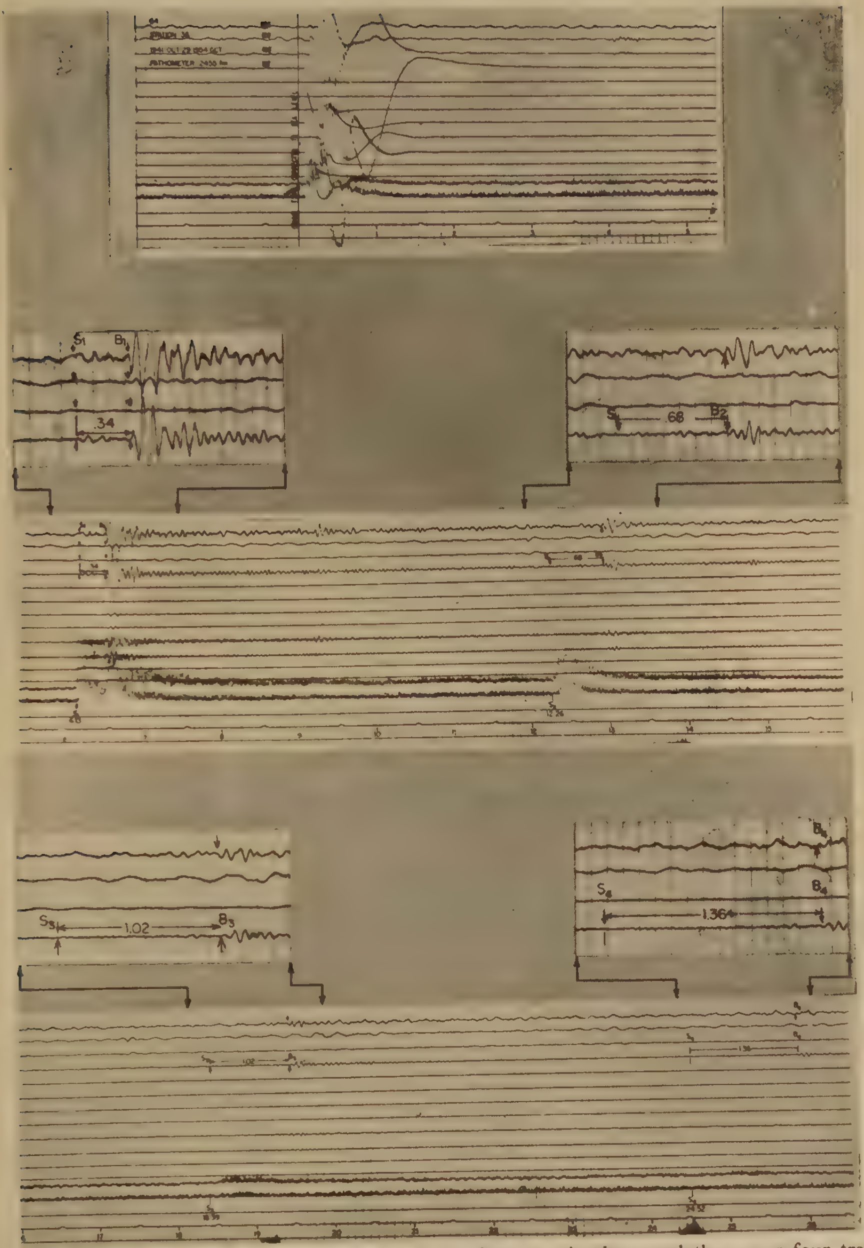

Fig. 2. Specimen reflexion record. The record has been cut in three and the upper four traces enlarged in four places. These four traces are low-frequency channels from four different hydrophones; the fourth trace has opposite polarity to the first three. Direction of first motion is shown by arrows. Traces 9 and 10 are band-pass; 13 and 14 are rectified high frequency.

(1.62)

" R " reflexions also occur. It will be noted that there is variation in polarity in the four hydrophones on the low-frequency traces: the first three have positive pressure down; the fourth, positive pressure up. The polarity of the first motion reverses with successive reflexions because of the reversal at each reflexion from the ocean surface.

Two groups of reflexions were found on the records. A set of tracings of one low-frequency trace from each of ten records, arranged from north to south, is shown in Fig. 3. The records are aligned on the time of the bottom reflexion. On this set can be seen one consistent arrival in the northern records; it appears to deepen to the south and on shots 36 and 40, it is preceded by an earlier arrival. Similar arrivals are found on the remaining records of the survey. In Fig. 4 are shown five records taken within a small area, showing variation with topography. Again, the records are aligned on the bottom reflexion time rather than the firing time so as to show variations of sediment thickness. Records 10 and 11 were taken over a small hill; records 13, 14, and 15 over an adjacent valley. It can be seen that the valley shots have the basement reflexion arriving about 0·05 sec later than the shots on the hill, indicating thicker sediment in the valley.

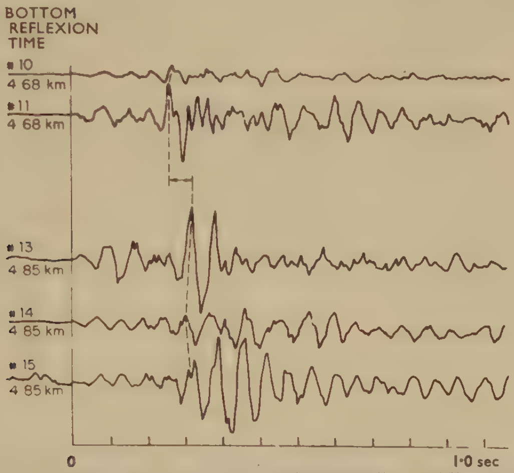

Fig. 4. Comparison of records from a hill and an adjacent valley. Alignment is in time of the first bottom reflexion. Dashed lines connect similar events.

These record profiles suggest that there is a variation of sediment thickness both from north to south and from hill to valley; in order to separate these effects without additional adjacent hill-valley combinations, it has been necessary to resort to statistics.

The records were timed by correlation of similar phases, and an attempt was made to pick the true beginning of the sub-bottom arrival. This is admittedly a subjective process, and there can be some difference in the times picked by different observers or by the same observer on different occasions. It is believed that the picks are at least consistent; they are plotted in Fig. 5.

A statistical fit has been made for linear variation of bottom-to-basement reflexion time interval as a function of latitude and water depth for the deeper (and more consistent) reflexion. The " plane of best fit " is expressed by the equation

$$t = 0{\cdot}33 - 0{\cdot}034L + 0{\cdot}21Z \pm 0{\cdot}04 \text{ sec} \qquad (1)$$

where

t = time from the sea-floor reflexion to the " basement " reflexion

L = variation of latitude from the mean (8·26°N)

Z = variation of sea-depth from the mean (4·562 km.)

The equation is, of course, applicable only over the zone of observations. It indicates that there is about 20 per cent more relief at the base of the sediment than at the top and a thinning of about 10 per cent of the mean for each degree of north latitude. The partial correlation coefficients are 0·89 for the latitude term; 0·48 for the depth term. If the separation of the reflexions into two groups is justifiable, there is a significant correlation of sediment thickness variation with both latitude and water depth. Even if the two groups of reflexions are combined for statistical analysis, the latitude term is still significant, although the significance of the depth term becomes marginal.

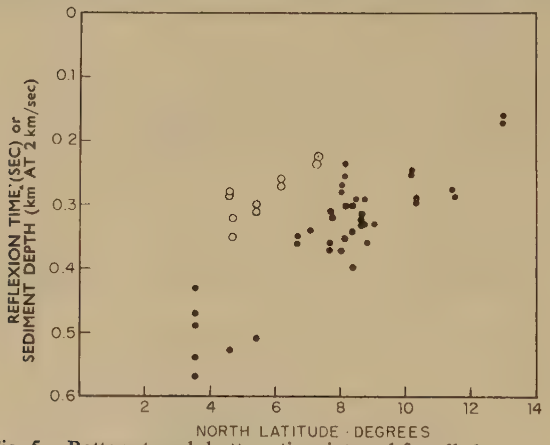

Fig. 5. Bottom to sub-bottom time interval for all shots.
○ first reflexion ● basement reflexion

The absolute sea-depth has been used above because it is amenable to statistical handling. Of greater geologic significance is a correlation with topographic position, if the cause of thickness variation is topographic control of the rate of accumulation. Five shots were located over hilltops; 14 over valley bottoms. Reflexion times, corrected for the latitudinal variation by the second term of equation (1) have means differing by 0·05 sec for the two groups; the difference of the means is significant at the 98 per cent confidence level.

The results of this analysis have been used to make the plot of Fig. 6 where the statistically determined term for variation with water depth has been removed, and the reflexion times have been plotted as a function of latitude alone. The straight line in the plot is the line of regression for latitudinal variation. If a velocity of 2 km/sec for the sediment is assumed, the plot may be considered a composite profile of sediment thickness in kilometres.

On the *Capricorn Expedition* strong reflexions were obtained at refraction stations C24 and C25, east of the reflexion profile (Raitt, 1956, and private communications).

At these stations the reflexion shots were fired at varying ranges out to the distance at which the refracted waves begin, making it possible to obtain velocities for the material above the reflecting horizon by $X^2 : T^2$ analysis. On station C24, the sediment velocity was 2·6 km/sec, and the depth obtained from reflexion and refraction data agreed closely. On station C25, the velocity in the material above the reflecting horizon was 2·1 km/sec, but the depths from reflexion and refraction disagreed. The reflexion was from a horizon well above the " basement " layer which produced the refracted arrival. When an adjustment is made for depth variation relative to the average of the lines of shooting using the factor in equation (1), the reflexion on C25 coincides closely with the shallow horizon of the reflexion lines, and the refraction arrival coincides with the deeper horizon. The data from these two stations have been entered on Fig. 6, and curves fitting the combined data appear as dashed lines. A similar section presented by ARRHENIUS (1958) for the first 15 m of sediment using

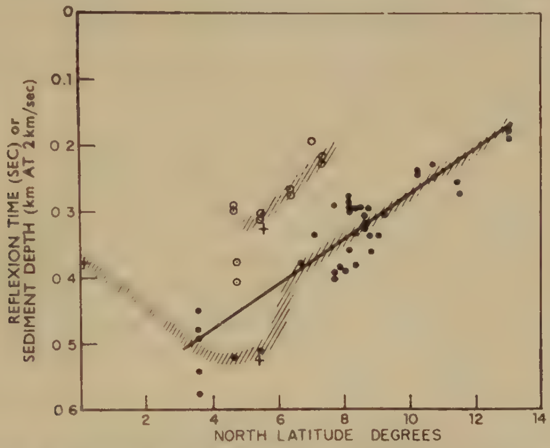

Fig. 6. Data adjusted for topographic position, using depth factor of equation (1); statistical fit entered as straight line, best curve also drawn. Stations from RAITT (1956) entered with topographic adjustment made.
○ first reflexion ● basement reflexion + data from RAITT (1956)

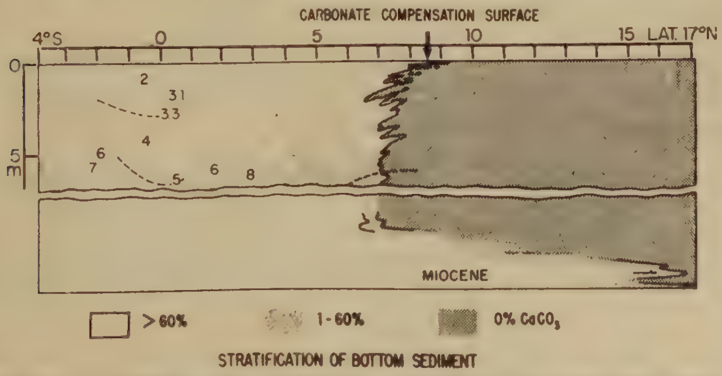
CARBONATE COMPENSATION SURFACE
4°S
0
5
10
15 LAT. 17°N
0
5
m
2
31
33
4
6
7
5
6
8
MIOCENE
>60%
1-60%
0% CaCO$_3$
STRATIFICATION OF BOTTOM SEDIMENT

Fig. 7. Sediment composition and stratigraphic correlation in the shallower material, from ARRHENIUS (1958).

evidence from core analysis is reproduced in Fig. 7 for comparison. The similarity is striking.

On Figs. 2, 3, and 4, the difference between the reflexion coefficients at the sea floor and the base of the sediments is very large. Such contrast is to a lesser extent true of the entire area studied and is the reason usable reflexion data can be obtained with relatively unsophisticated methods. Average low-frequency reflexion coefficients were determined from those records which showed multiple reflexions; they were 0·3 for the water-sediment interface and 0·7 for the deeper reflexions. There was no significant difference between the coefficients for the arrivals from the base of the sediments and from the horizon within the sedimentary section. These reflexion coefficients are compatable with the velocities near 2 km/sec for the sediments and 5 km/sec for the basement determined by other methods. They imply that the best explanation for the reflexion from within the sedimentary section is that it comes from material with density and velocity close to that of the " basement " that is too thin and discontinuous to appear as a refracted wave.

GEOLOGICAL SIGNIFICANCE

The thickened sediment found in the valleys could arise from several causes. Turbidity-current deposition from distant sources could produce this effect; it is believed, however, (Arrhenius, 1952) that the area is completely shielded from these. A much more probable cause is local movement of material from hills to valleys by current action or solifluction. The report of Tertiary sediments outcropping or covered by a thin stratum of Pleistocene-Recent material on topographic highs in this area (Arrhenius, op. cit.) is added evidence.

The thickening of the sediment occurs near the boundary of the zone of high carbonate deposition as described by Arrhenius (1952) and shown in Fig. 1 and Fig. 7. This implies that the conditions now prevailing have existed for some time in the past. Extrapolation of rates of accumulation of oceanic sediment is dubious at best, but using rates given by Arrhenius for recent sedimentation in this area, one can at least say that high carbonate deposition in the southern part of the area has existed for some tens of millions of years. This thickening of the sedimentary section to the south is entirely sufficient to account for the shoaler average ocean depth south of the Clipperton Fracture Zone; the implication is that in this area the shoaling is a result of carbonate deposition rather than the reverse.

Acknowledgement—This work was supported by the Bureau of Ships and the Office of Naval Research under contracts with the University of California. Max Silverman fired the charges, Alan Jones prepared the equipment, Gloria Slack and Wanda Wilson aided in some of the computation, Edward Goldberg and Gustaf Arrhenius gave much helpful discussion of the problems. Russell W. Raitt provided the results of the *Capricorn Expedition* work and has aided in the project throughout.

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(166)

REFERENCES

Arrhenius G. (1952) Sediment Cores from the East Pacific. *Reps. Swedish Deep Sea Expedition* 1947-1948, **5**, 1-227.

Arrhenius G. (1958) *Sedimentation on the ocean floor in Current Topics in Geochemistry*, Ed. P. H. Abelson, McGraw-Hill, New York.

Hersey J. B. and Ewing M. (1949) Seismic reflections from beneath the ocean floor. *Trans. Amer. Geophys. Union*. **30**, 5-14.

Menard H. W. and Fisher R. L. (1958) Clipperton fracture zone in the north-eastern equatorial Pacific. *J. Geol.* **66**, 239-253.

Raitt R. W. (1956) Seismic-refraction studies of the Pacific ocean basin. Part I: Crustal thickness of the central equatorial Pacific. *Bull. Geol. Soc. Amer.* **67**, 1623-1639.

Printed in Great Britain by The Salisbury Press Ltd., Publicity House, Wilton Road, Salisbury, Wilts. (15662)

Deep-Sea Research, 1959, Vol. 5, pp. 306 to 309. Pergamon Press Ltd., London. Printed in Great Britain

INSTRUMENTAL NOTE

Effect of pressure upon the "protected" oceanographic reversing thermometer

(*Received* 22 *September* 1958)

INTRODUCTION

Actual degree of protection offered by the shell of the usual "protected" reversing thermometer has been computed. It appears that in the average modern instrument errors of roughly 0·002° C per 1,000 m sea depth change can be expected. However, certain protected instruments having an exceptionally small air volume below the cork have been found to be influenced by external pressure changes to as much as 0·008° per 1,000 m particularly at great sea depths.

The oceanographic reversing thermometer of the so-called "protected" type is enclosed in a heavy glass cylinder, and because of this, it is relatively insensitive to change in external pressure. Nevertheless, it is not safe for the oceanographer to completely ignore pressure effects whenever the protected thermometer is to be used with precision at great depths. Direct test of protected instruments for hydrostatic errors is not easy and apparently is seldom done, however, the approximate magnitude of these errors may be computed from instrument dimensions and from the elastic properties of the glass protective cylinder. Such computations indicate (1) that the pressure effect frequently lies just below the magnitude of usual significance, but (2) that under certain circumstances these pressure errors may exceed what is tolerable.

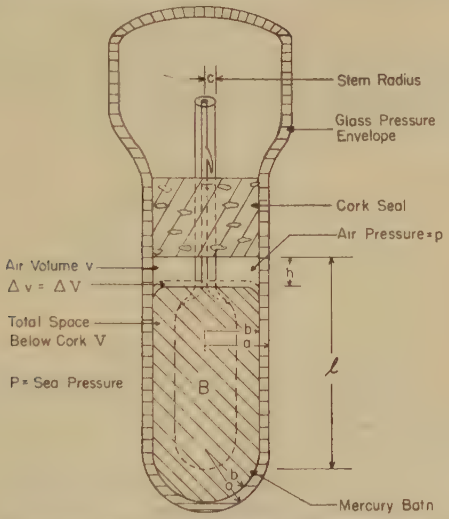

Fig. 1. The lower end of the usual "protected" reversing thermometer; the dimensions involved in a consideration of pressure error.

Fig. 1 presents the physical features involved. An increase of external pressure ΔP causes a decrease in interior dimensions of the sealed space below the cork and therefore a decrease in air volume Δv. Because of the compression of this air, a pressure at the outside surface of the thermometer bulb B is increased by Δp.

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From the gas laws it can be shown that :

$$\Delta p = \frac{p_1 \, \Delta V}{v_1 - \Delta V} \qquad (1)$$

where p_1 = initial gas pressure

and v_1 = initial gas volume (where the subscript is to mean an initial condition),
and ΔV = the change in total volume below the cork; which is also the decrease in air volume, i.e. Δv.

Now this gas pressure change Δp squeezes a small amount of mercury from bulb B into the reading stem ; that is, it causes an apparent temperature increase $\Delta T'$. A numerical relationship can be obtained from the data relating to the " unprotected " thermometer where it is customary to express the pressure deviation.

$$\Delta T' = Q \Delta Z \qquad (2)$$

where Q is an instrument constant and,
where Z is sea depth in metres. Converting thus to equivalent pressure units,

$$\Delta T' = 10\, Q \Delta p \qquad (3)$$

where p is the pressure (atm) external to bulb, B.
Combining equations (1) and (3) gives for the pressure error :

$$\Delta T' = \frac{10\, Q p_1 \, \Delta V}{v_1 - \Delta V} \qquad (4)$$

A reasonably approximate value of ΔV as a function of a change in external sea pressure ΔP can be deduced from the classical solutions for the compression of a thick-walled cylinder and for an end cap consisting of a thick-walled spherical shell since efforts usually are made by the glass blower toward maintaining these simple configurations. It can be shown (LAMB, 1916) that, approximately,

$$\Delta V = \frac{\pi}{E} \left[(5 - 4\sigma) \frac{a^2 b^2 l}{a^2 - b^2} + 3(1 - \sigma) \frac{a^3 b^3}{a^3 - b^3} \right] \Delta P \qquad (5)$$

where the first term refers to a cylinder of length l, and the second term refers to the spherical end cap. The external and internal radii are a and b, respectively. E is Young's modulus, and σ is Poisson's ratio of the glass of the shell.

Numerical examples

For the physical properties of one common type of glass used in thermometers :

$$E = 6 \times 10^8 \text{ g/cm}^2 \text{ and,}$$

$$\sigma = 0{\cdot}25$$

For this glass, equation (5) reduces to :

$$\frac{\Delta V}{\Delta P} = 2{\cdot}1 \times 10^{-8} \left(\frac{a^2 b^2}{a^2 - b^2} \right) l + 1{\cdot}2 \times 10^{-8} \frac{a^3 b^3}{a^3 - b^3}, \qquad (6)$$

where ΔP now is in g/cm^2 (i.e., cm of water roughly).

Case A : (for the dimensions of an average protected instrument)

Measurements were made upon several modern protected thermometers. In frequent instances, the following dimensions were representative :

$$a = 0{\cdot}75 \text{ cm}$$

$$b = 0{\cdot}60 \text{ cm}$$

$$c = 0{\cdot}20 \text{ cm}$$

$$l = 4{\cdot}5 \text{ cm}$$

$$h = 0{\cdot}6 \text{ cm}$$

from which the initial air volume is,

$$v_1 = 0{\cdot}6 \text{ cm}^3$$

From these can be computed from equation (6)

$$\Delta V = 10^{-7}\, \Delta P = \text{cm}^3 \qquad (7)$$

where ΔP is in g/cm^2.
Substituting for ΔV in equation (4) gives, for the common instrument,

$$\Delta T' = \frac{Qp_1\, \Delta P}{v_1 - \Delta V} \times 10^{-6}, \qquad (8)$$

which further reduces to,

$$\Delta T' = \frac{Qp_1\, \Delta Z \times 10^{-1}}{0{\cdot}6} \text{ approximately} \qquad (9)$$

where ΔZ is changed to sea depth in 1,000 metre units.

Factors Q and p

The numerical value of p_1 depends upon the amount of compression given the air during the driving in of the cork, and upon the amount which has since diffused away. It is likely p_1 is nearly 1 atm in most older instruments, although in certain new ones it might temporarily amount to twice this, or even more. In passing it might be well to point out that equation (8) gives reason for the suspicion that in the protected reversing thermometer at least part of the well known zero point shift with age could be due to slow changes in p_1.

The factor Q can be measured by a non-destructive test involving breaking the mercury thread in an unusual manner. A few of such measurements have been made, and these have resulted in numerical values not greatly different from the values found for unprotected thermometers. It appears that Q should be not smaller than about 0·01°/m head of water.

Using these estimates for p_1 and Q in equation (9), the rate of deviation due to depth can be estimated as

$$\frac{\Delta T'}{\Delta Z} = 0{\cdot}002° = \text{degrees/1,000 m depth change,} \qquad (10)$$

with the major uncertainty resting in the values used for Q and p. Thus in the case of the usual modern instrument this error is a constant of the instrument which is practically independent of depth.

Conclusions regarding the averaged protected thermometer

Since it seems likely that p and Q each may in certain specimens reach values twice the value used in equation (9), there is no certainty that pressure errors as much as perhaps 0·01°/1,000 m depth change do not actually arise during ordinary oceanographic casts.

Case B : *Special circumstances (an overfilled thermometer used at great depths)*

Inspection of equation (4) will show that the pressure error is most likely to be significant whenever the pressure is large (i.e., ΔV is large), and also whenever the shell is overfilled with mercury (i.e., v_1 is small).

One special protected thermometer which had actually been used at about 7 km depth was discovered to have an abnormally small air volume. Other parameters apparently were about the same as those listed in Case A above, however in this instrument,

$$v_1 = 0{\cdot}16 \text{ cm}^3.$$

In this instance, and if the same nominal values for p and Q used above are assumed, the pressure deviation would have the rates :

0·006° C	between 0 and 1 km
0·007° C	between 4 and 5 km
0·008° C	between 6 and 7 km

In this case the increase in error with depth is due to the effect of V in the denominator in equation (4) ; it is physically possible for the denominator to approximate zero at very high external pressures.

A duplicate of this particular instrument was exposed to a hydrostatic test of 18,000 lb/in^2 while it was lying horizontal. The observation that part of the mercury in the bath was extruded through the cork seal under this exceptionally high squeeze induced thoughts as to the origin of this behaviour and thereby initiated the foregoing study.

From the above it would appear that a study of deep gradients with reversing type of thermometer should include a correction for the effect of pressure on the protected instruments and that special caution should be taken whenever comparing instruments differing in physical construction.

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REFERENCES

Lamb H. *Statistics*, Cambridge University Press, 1st Ed., Chapter XVIII, 1916.

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Acoustical Absorption Arising from Molecular Resonance in Solids*

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(Received May 26, 1958)

Resonance phenomena resulting in anomalously high acoustic absorption can occur whenever lattice and internal molecular vibrational frequencies overlap. Significant effects are predicted at all acoustic frequencies, without restriction to the resonance region. A method is given for calculating resonance absorption using available molecular constants. As an illustrative example, the magnitude of resonance absorption has been calculated for benzene. The predicted absorption is 0.5 cm^{-1} at the 10-Mc/sec frequency, orders of magnitude larger than have been observed in other single crystals. In order to test this prediction, measurements of absorption were made on a large single crystal of benzene yielding at 10 Mc/sec, 0.25 cm^{-1}. This agreement between absorption and calculated values is considered adequate, confirming the phenomenon.

INTRODUCTION

A MOLECULAR crystal exhibits two classes of thermal oscillations: those in which each molecule vibrates as a whole about its lattice position; and the internal vibrations of the atoms comprising the molecule. Although lattice vibrational frequencies are generally lower than internal vibrations, it is quite possible that higher lattice vibrational frequencies may overlap the gravest internal vibrational mode. Because some coupling always exists between these vibrational modes, an overlap in frequency results in resonance. One of the concomitant phenomena in mechanically resonant systems is the slow transfer of energy. For example, two weakly coupled pendula exchange oscillations only if they are close to resonance; but the closer to resonance, the slower the exchange of energy. Similarly, the rate of energy transfer between lattice and internal oscillations is slow; and thermal equilibrium is achieved relatively slowly.

Crystalline substances possessing this resonance property should exhibit the phenomenon of a time-dependent specific heat. In particular, for a periodic temperature variation of frequency ω, the specific heat will be of the form, $c=c_0+c'/(1+i\omega/\kappa)$; the parameter, κ, is the number of transitions per unit time; its reciprocal is the relaxation time of the process. The complex character of c expresses the phase lag between the applied temperature and internal thermal oscillations; the real part of the specific heat is in phase with the temperature while the imaginary part lags by $\pi/2$.

A substance having a complex specific heat also has a complex velocity of sound; stated in another way, the wave number of an acoustical wave will be complex. Since the imaginary part of the wave number is the negative of the absorption coefficient, it can be shown that absorption is given by[1]

$$\alpha=\frac{1}{2V}\frac{(c_p-c_v)}{c_p}\frac{c'}{(c_p-c')}\frac{\omega^2\kappa}{(\omega^2+\kappa^2)}, \tag{1}$$

where V is the velocity of sound.

Acoustical frequencies are always much smaller than the transition rate κ; hence the magnitude of the absorption will be inversely proportional to κ. Referring again to the two-pendula model, it is apparent that the weaker the coupling, the slower the rate of energy exchange. Hence, the acoustical manifestations of this phenomenon should be most apparent in molecules having weak coupling between lattice and internal vibrations.

The coupling of internal and lattice vibrations has been used by Pauli, Born, and others to explain the broadening of optical absorption lines in crystals at the dispersion frequency[2] and as an explanation of thermal conductivity in electrical insulators.[3] However, the possibility that mode coupling could be strongly manifested in acoustic absorption appears to have been overlooked. Landau and his colleagues[4] did consider the case of acoustic absorption resulting from coupling of the acoustic wave with the lattice vibrations, but this is a negligible effect except at extreme ultrasonic frequencies.

The ensuing discussion gives a method for the prediction of acoustic absorption in actual molecular crystals. It is shown that resonance absorption is not a negligible effect in molecular solids but can be orders of magnitude larger than other absorptive processes; as a confirming example, experimental observations on crystalline benzene are presented.

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* This work received support from the Bureau of Ships, Navy Department; Contribution from the Scripps Institution of Oceanography, New Series. 1080

[1] See, for example, W. T. Richards, Revs. Modern Phys. 11, 36 (1939).

[2] M. Born and K. Huang, *Dynamical Theory of Crystal Lattices* (Oxford University Press, London, 1954), p. 341.

[3] R. E. Peierls, *Quantum Theory of Solids* (Oxford University Press, London, 1955), p. 40.

[4] L. Landau and L. Rumer, Physik Z. Sowjetunion 11, 18 (1937).

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CALCULATION OF THE RATE OF TRANSITION

Oscillator Coupling

The coupling of lattice vibrations with internal oscillations is associated with the nature of intermolecular forces. For example, if these were Hooke's law forces, lattice vibrations would be strictly harmonic and no coupling could result. The actual intermolecular binding forces in molecular crystals are van der Waals' forces which depart considerably from Hooke's law. A good approximation for molecular crystals is given by the Lennard-Jones potential, a function having wide application in the liquid and gaseous state. The binding energy is thus taken to be

$$U(r)=-4\epsilon[(r_0/r)^6-(r_0/r)^{12}]. \tag{2}$$

The above potential is for two molecules with no neighbors. The effect of adding additional neighbors in the crystal lattice is readily deduced in the following elementary argument: The potential of a single molecule with two nearest neighbors all in line at spacing, d, is simply the summation of two pairs: $W(r)=U(r)+U(2d-r)$; transforming in terms of a small displacement from equilibrium, ζ, this potential becomes

$$W=W_0+U_{r=d}''\zeta^2+U_{r=d}^{\mathrm{IV}}\zeta^4/12+\cdots.$$

The cubic term vanishes since W is even. The potential for displacement perpendicular to the molecular line is

$$\Delta W=U'\zeta^2/d+U''\zeta^4/4d^2+\cdots.$$

Hence a three-dimensional, simple cubic lattice of six nearest neighbors with spacing, d, has the potential

$$\Delta W=(U''+2U'/d)\zeta^2+(U^{\mathrm{IV}}/12+U''/2d^2)\zeta^4+\cdots. \tag{3}$$

The first term in each of the brackets corresponds to displacement along the trimolecular line; the second term is the transverse oscillation, involving two pairs of neighbors. Because of symmetry, this expression remains approximately valid for any direction. Anharmonicity results from quartic and higher even-power terms in ζ, and hence these are the important terms which lead to coupling.

Coupling becomes analytically more amenable when transformed to normal coordinates. Following the usual procedure, the coordinate ζ is transformed to a principal coordinate in which the significant motion separates into motion of the center of the molecular mass and motion of the atoms, $\zeta=X+x$, where X is the molecular, and x, the atomic coordinate. The anharmonic coupling potential (neglecting higher than quartic terms) is then

$$H'=A(X+x)^4\simeq 4AX^3x, \tag{4}$$

where

$$A=U^{\mathrm{IV}}/12+U''/2d^2.$$

The omitted terms in the above expansion are insignificant inasmuch as the atomic displacement is certainly small compared to the lattice motion. This expression for the coupling energy obviously represents a considerable idealization for a three-dimensional lattice will, in general, have different elastic constants for different crystal directions. Furthermore, the coordinates X and x are in general not collinear, and some correction factor between $\frac{1}{2}$ and unity should be included. In spite of these approximations the results indicate that the accuracy of the calculation is adequate for the present; the predicted acoustical absorption is a large effect, and absorption measurements are rarely precise.

Transition Probability

Although the calculation of the relaxation time between the two oscillators may be considered a classical one solvable by the usual procedures of classical mechanics, the procedures of quantum mechanics more readily lend themselves to this calculation. For example, in quantum mechanics the transition probability per unit time is a familiar perturbation calculation, given in the form[5]

$$\kappa=t^{-1}\int aa^*\rho(k)dE_k, \tag{5}$$

where

$$a(t)=(i\hbar)^{-1}\int_{-\infty}^{t}H_{01}'\exp(2\pi i\nu_{01}t)dt.$$

As interpreted here, the internal oscillators make transitions between the two quantum states, 0 and 1; the frequency associated with this transition is ν_{01}. Neglect of transitions to higher states corresponds classically to neglect of higher powers of x in Eq. (4) above. The quantity H_{01}' is the matrix element of the transition defined by $H_{01}'=\int\psi_0H'\psi_1dx$ where ψ_0 and ψ_1 are the simple harmonic oscillator wave functions for the states 0 and 1. Utilizing the expression for the coupling potential H' from Eq. (4), the quantity a becomes

$$a=4AX_0^3(i\hbar)^{-1}\int_{-\infty}^{\infty}\psi_0\psi_1xdx\int_{-\infty}^{t}\sin^3(2\pi\nu t) \times\exp(2\pi i\nu_{01}t)dt, \tag{6}$$

where X is considered a classical dynamical variable of the form $X=X_0\sin(2\pi\nu t)$. The integration with respect to time leads to

$$a=\frac{AX_0^3}{2ih}\left[\frac{1-\exp(2\pi it)(3\nu+\nu_{01})}{3\nu+\nu_{01}}+\frac{1-\exp(2\pi it)(\nu_{01}-3\nu)}{\nu_{01}-3\nu}+\frac{1-\exp(2\pi it)(\nu+\nu_{01})}{\nu+\nu_{01}}+\frac{1-\exp(2\pi it)(\nu-\nu_{01})}{\nu-\nu_{01}}\right]\int_{-\infty}^{\infty}\psi_0\psi_1xdx. \tag{7}$$

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[5] For example, see L. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1949), Sec. 29.

Of the four terms in this equation only the second and fourth are important, and these only if $\nu_{01} \simeq \nu$ and/or $\nu_{01} \simeq 3\nu$. Thus the rather unusual situation obtains with resonance occurring whenever a single quantum of the internal frequency exchanges with either 1 or 3 quanta of the lattice frequency. If each of the molecular coordinates, X, in the coupling potential had been considered independent ($X_1X_2X_3$ instead of X^3), then the resonance would have been restricted to the three quanta exchange, $\nu_{01} \simeq 3\nu$. Actually in all molecules for which data exists, ν_{01} is much larger than the maximum ν, and normal resonance, $\nu_{01} \simeq \nu$, is probably unimportant even if the coordinates X are not independent. This unusual resonance phenomenon may also be described alternatively in terms of phonon collisions; in this case collisions between three lattice phonons and a single internal phonon are required in order that energy and momentum shall be conserved.[3,6]

The remaining integration (with respect to the coordinate x) leads to[7]

$$aa^* = \frac{A^2 X_0^6 \sin^2[\pi i(\nu_{01} - 3\nu)t]}{4h^2\alpha(\nu_{01} - 3\nu)^2}. \tag{8}$$

As ordinarily interpreted, Eq. (5) implies resonance with any *single* upper state for effecting transition. In that case, the quantity $\rho(k)dE_k$ in Eq. (5) is ordinarily defined so that it represents the fraction of lattice states taken *singly* (or single lattice phonons) with energy lying between E_k and $E_k + dE_k$. However, the above discussion demonstrates that three lattice states (or three lattice phonons) are necessary to effect transition. The distribution function of lattice states, taken in sets of three in the energy range dE_k, is then $[\rho(k)dE_k]^3$. The modified form of Eq. (5) for this case then becomes

$$\kappa = t^{-1} \int\int\int aa^*[\rho(k)dE_k]^3$$

$$= \frac{A^2X_0^6}{4h^2\alpha t} \int\int\int \frac{\sin^2[\pi i(\nu_{01} - 3\nu)t]\rho^3(k)dE_k^3}{(\nu_{01} - 3\nu)^2}. \tag{9}$$

The value of the single integral involving the sine function is small except in the region of resonance so that its integration limits can be extended from $-\infty$ to $+\infty$, a familiar definite integral. Integrating once, yields

$$\kappa = (\pi^2 A^2 X_0^6 h / 12\alpha) \int\int \rho^3(k) d\nu^2, \tag{10}$$

which leaves only the problem of evaluating the energy density, $\rho(k)$.

In the Debye theory of specific heats, the distribution of lattice vibrations is taken to be $dN = (3/\nu_m^3)\nu^2 d\nu = \rho(k)dE_k$ or $\rho(k) = 3\nu^2/h\nu_m^3$, where the parameter ν_m is the maximum lattice frequency as interpreted by Debye. The limits of the remaining integrals above are therefore taken from 0 to ν_m. Hence, the final result obtains:

$$\kappa = \frac{9A^2(kT)^3N^4}{16h\nu_{01}m_{01}\nu_m^7(4\pi^2M)^3}, \tag{11}$$

where X_0 has been replaced by its classical value $X_0 = (kT/4\pi^2M\nu^2)^{\frac{1}{2}}$; the molecular weight is M, and N is Avogadro's number.

It will be noted that this result is sensitive to two parameters: the quantity A, determined from the Lennard-Jones potential constants, a measure of the strength of the intermolecular binding forces; the parameter ν_m, interpreted in the original Debye theory as a lattice vibration. If ν_m is truly related to lattice vibrations, it might be expected that it is not independent of the parameter A. However this interpretation remains speculative, and ν_m can best be considered an empirical parameter determined from specific heat data. Although Planck's constant h appears explicitly, the calculation is not dependent fundamentally upon quantum mechanics; it will be noted that the product $h\nu_{01}$ occurs in the denominator corresponding classically to the energy of the internal oscillator.

AN ILLUSTRATIVE EXAMPLE: BENZENE

A small value for the transition probability, κ, leads to large acoustic absorption. Hence, the phenomenon of resonance absorption should be most readily observable in substances for which Eq. (11) leads to a small value. Such substances might in general be expected to be characterized by (1) a relatively large molecular weight, (2) a large fundamental vibrational frequency, and (3) a large Debye frequency. However, these first two characteristics are in general in opposition and their combined effect may not be relatively important. Probably of considerable importance is the requirement that A is small, or the binding forces weak; this implies that the Lennard-Jones parameters ϵ and r_0, are small and the intermolecular spacing large.

An illustrative example, benzene, was selected for study. This substance is almost the ideal molecular crystal. Simpler molecules exist, but benzene is probably the simplest molecular substance existing in the solid state which can be studied over the wide temperature range necessary to establish accurate specific heat data; no complications arise out of polymorphic transitions, molecular disorder, or hydrogen bonding. Raman and infrared spectra have been studied extensively as well as intermolecular potentials leading to the Lennard-Jones parameters.

The values for benzene for evaluation of the transition probability are given in Table I. Substitution in Eq.

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[6] E. Bauer, J. Chem. Phys. 26, 1440 (1957).

[7] The simple harmonic oscillator wave functions are

$$\psi_0 = (\alpha/\pi)^{\frac{1}{4}} \exp(-\alpha x^2/2),$$
$$\psi_1 = (\alpha/\pi)^{\frac{1}{4}} 2(\alpha)^{\frac{1}{2}} x \exp(-\alpha x^2/2),$$

where $\alpha = 4\pi^2 m_{01}\nu_{01}/h$.

(11) leads to $\kappa = 10^9$/sec; this is rather a low value compared to transition probabilities in other processes. The predicted acoustic absorption utilizing Eq. (1) together with this transition probability is about 0.5 cm^{-1} at 10^7 cps; resonance absorption will vary as the square of the frequency. Hence absorption arising from resonance is orders of magnitude greater than has thus far been observed in crystals (e.g., quartz, metals).

TABLE I. Numerical constants for benzene.

ϵ (Lennard-Jones parameters)[a]	6.15×10^{-6} erg
r_0	5.27×10^{-8} cm
d (intermolecular spacing)[b]	5.03×10^{-8} cm
$A(\epsilon, r_0, d)$ (coupling parameter)	1.73×10^{20} g cm^6/sec^2
ν_m (Debye frequency)[c]	3.1×10^{12} sec^{-1}
ν_{01} (internal vibrational frequency)[d]	1.21×10^{13} sec^{-1}
M (molecular weight)	78.11 g
m_{01} (apparent internal vibrating mass)[d]	24 g
T (temperature)	273°K

[a] Hirschfelder, Curtis, and Bird, *Molecular Theory of Gases and Liquids* (John Wiley and Sons, Inc., New York, 1954), p. 1112.

[b] E. R. Andrew and R. G. Eades, Proc. Roy. Soc. (London) **A218**, 537 (1953).

[c] Lord, Ahlberg, and Andrews, J. Chem. Phys. **5**, 649 (1937).

[d] R. C. Lord, Jr., and D. H. Andrews, J. Phys. Chem. **41**, 149 (1937).

In order to test this prediction, a large single crystal of benzene of linear dimensions about 7 cm was grown from the purified liquid and its acoustic absorption measured. The details of the method of crystal growth and acoustic measurement are to be published elsewhere.[8] The measured absorption of longitudinal acoustic waves at 10^7 cps was found to be 0.24 cm^{-1}. At frequencies around 6.4×10^6 cps the absorption was 0.09 cm^{-1}. In the frequency range measured, the frequency dependence was proportional to ω^2 as predicted. As a check on the experiment, measurements on a sample of ice obtained from a block of commercial ice of rather poor optical quality yielded 0.04 cm^{-1} at 10^7 cps. In view of the many approximations inherent in the theory, this agreement between observation and theory is considered adequate.

DISCUSSION

The above calculation is capable of considerable refinement. The crystal symmetry of benzene is not simple cubic, as assumed, but simple orthorhombic (*Pbca*); nor does a single acoustic wave propagate, but longitudinal and transverse waves may exist, each with characteristic elastic constants in the three crystallographic axes. Further, the Lennard-Jones potential is a central force field intended for spherically symmetric molecules; in addition the constants used were determined from the vapor rather than the crystalline state. In spite of these obvious simplifications, the immediate result is meaningful. The predicted and observed absorption is orders of magnitude higher than has been observed in other crystalline substances (in which resonance absorption is believed to be negligible). The major source of acoustic dissipation in solid benzene, and undoubtedly in many other substances, is certainly resonance absorption.

It would be of interest to search for additional examples of resonance absorption in molecular crystals. Tabular values of Lennard-Jones coefficients for other molecules indicate that the coupling coefficient A is comparable to that in benzene in a number of other simple organic substances. With the aid of a more precise theory, measurements of acoustic absorption may well yield significant molecular properties.

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[8] L. Liebermann, J. Acoust. Soc. Am. (to be published).

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Method for Obtaining the Optical Properties of Large Bodies of Water*

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Abstract—Radiative transfer within a hydrosol such as ocean or lake water can best be described by means of the inherent and apparent optical properties of the hydrosol. Equipment for obtaining the important optical properties of large bodies of water is described and a method for computing six optical properties from measurements of radiance distribution is given.

The optical properties of Lake Pend Oreille are computed for one condition of the lake and for one narrow region of the spectrum. The experimental values serve to substantiate certain theoretical relationships between the inherent and the apparent optical properties.

Introduction—In order to deal exactly with problems involving the penetration and transfer of light through water, it is necessary to specify not only the magnitudes of the optical properties but also the depth at which they are measured and whether they depend on the downwelling (−) or upwelling (+) stream of radiant flux. This is necessary because some of the optical properties of homogeneous water vary with depth, although the variation may be small. In order to be exact in meaning, the notation for the optical property or function is followed by the symbol (z) which means we are speaking of the property at a specific depth, z, and with the symbol (−) referring to properties associated with the downwelling stream of radiant flux or (+) referring to the upwelling stream of radiant flux.

In general the variation of the properties tends to diminish with increasing depth and with increasing cloud cover and overcast. When the water is nonhomogeneous the usual variation with depth of the optical properties may be obscured by the further variations caused by this nonhomogeneity.

List of symbols—The notation used in this paper is as follows:

$N(z, \theta, \phi)$	Field radiance at depth z in direction (θ, ϕ)
N_r/N_0	Ratio of the radiance of a beam after passage through a water path of length r to its initial radiance
$h(z, -)$	Downwelling scalar irradiance at depth z
$H(z, -)$	Downwelling irradiance at depth z
$h(z, +)$	Upwelling scalar irradiance at depth z
$H(z, +)$	Upwelling irradiance at depth z
T_r	Beam transmittance for path of length r
$s(z)$	Total scattering function* at depth z
$D(z, -)$	Downwelling distribution function
$D(z, +)$	Upwelling distribution function
$R(z, -)$	Reflectance of downwelling light by a hypothetical horizontal plane in the water at depth z
$K(z, -)$	Attenuation function for downwelling irradiance
$K(z, +)$	Attenuation function for upwelling irradiance
$a(z)$	Volume absorption function at depth z*
$\alpha(z)$	Volume attenuation function at depth z*

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* In homogeneous media the term "function" as applied to these properties is replaced by the term "coefficient," since in homogeneous media these properties do not change with depth. The other functions generally vary with depth even in homogeneous media.

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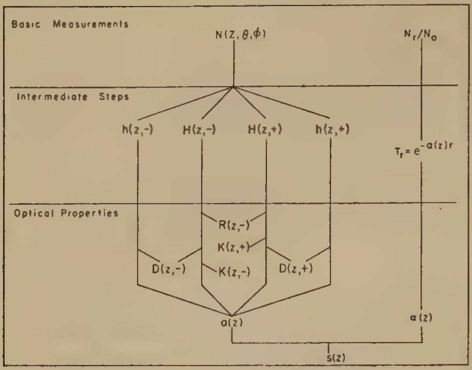

FIG. 1—Flow chart of optical constants and properties. The computational route is found by following the connecting lines in an upward direction from the desired optical constant or function

The important optical properties considered in this paper are shown in Figure 1 which also indicates in flow chart form one possible method of their determination from two basic physical measurements which were made at Lake Pend Oreille, Idaho [*Tyler*, 1958]. The two measurements were (a) radiance distribution as a function of depth, $N(z, \theta, \phi)$, and (b) beam transmittance, T_r.

Measurement of radiance distribution—The instrument used for the measurement of radiance distribution is shown in Figure 2 [*Duntley* and others, 1955]. When in use, this instrument is suspended on a single cable and powered by an electric cable looped into the underside at the vertical axis of rotation. Rotation about the vertical axis (azimuth position) is controlled by means of a servo system consisting of a gyrosyn compass assembly in the instrument with control transformer and indicator on the main control panel. The error signal resulting from an azimuth mismatch between the control transformer and the gyro heading is used to drive a propeller which rotates the instrument so as to minimize the error signal and thus keep the instrument oriented in azimuth. The optical system is designed to accept light through a cone of acceptance having apex angle of 6.6°, and the instrument thus measures relative values of the physical quantity radiance in the direction specified by θ (the angle from the zenith) and ϕ (the azimuth angle).

Data obtained with this instrument and the method of integration outlined in the next sections were used to compute the apparent optical properties $R(z, -)$, $K(z, -)$, $K(z, +)$, $D(z, -)$, and $D(z, +)$ for Lake Pend Oreille, and also the inherent optical property $a(z)$ (volume absorption function).

Computation of $H(z, -)$ and $H(z, +)$ from $N(z, \theta, \phi)$—It is clear from Figure 1 that the functions $H(z, -)$, $H(z, +)$, $h(z, -)$, and $h(z, +)$ are essential to the determination of the functions $R(z, -)$, $K(z, -)$, $K(z, +)$, $a(z)$, $D(z, -)$, and $D(z, +)$. The basis for obtaining irradiance on a horizontal plane from radiance distribution data is expressed in equation (1)

$$H(z, \pm) = \int_{\mp} N(z, \theta, \phi)\, |\cos \theta|\, d\Omega \qquad (1)$$

where $\int_{\mp}$ signifies integration over the upper $(-)$ or lower $(+)$ hemisphere to obtain respectively $H(z, -)$ or $H(z, +)$. Stated precisely

$$\int_{-} = \int_{\theta=0}^{\pi/2} \int_{\phi=0}^{2\pi} \qquad \int_{+} = \int_{\theta=\pi/2}^{\pi} \int_{\varphi=0}^{2\pi}$$

$$d\Omega = \sin \theta \, d\phi \, d\theta$$

In order to perform the numerical integration expressed in (1) and thus obtain numerical values for $H(z, -)$ and $H(z, +)$, the radiance distribution solid was enclosed in a spherical grid divided by equal increments of θ and ϕ. The values of radiance at the centers of these increments were then weighted and summed in accordance with (2).

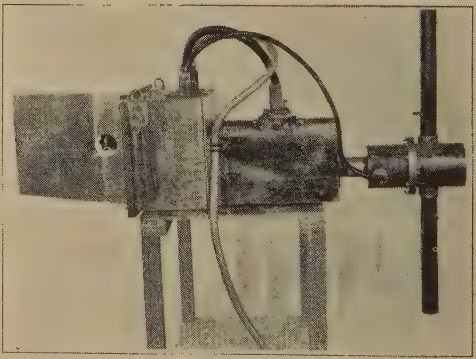

FIG. 2—Underwater photometer showing the radiance measuring head on the right and azimuth control propeller on the left

The mechanics of the integration process at a given depth can be expressed in symbols as

$$H = \sum_{i=0}^{m} \sum_{j=0}^{n} N_{ij}\, \Delta\Omega_i' \qquad (2)$$

where N_{ij} is the value of the radiance at the center of the increment specified by i in the θ direction and j in the azimuth direction. $N_{0j} = N_{00}$ for $j = 0, 1, \cdots, n$; since the radiance in the zenith direction does not change with azimuth; and where the $\Delta\Omega_i'$ are weighted solid angles defined for the indicated zones ($i = 0, 1, \cdots, m$) as follows

$$\Delta\Omega_i' = \sin\theta_i \cos\theta_i\, \Delta\theta\, \Delta\phi, \qquad \text{for} \quad i = 2, 3, \cdots, m-2$$

$$\Delta\Omega_0' = \Delta\Omega_m' = \tfrac{3}{8} \sin\left(\frac{\Delta\phi}{4}\right) \cos\left(\frac{\Delta\phi}{4}\right) \Delta\theta\, \Delta\phi$$

$$\Delta\Omega_1' = \Delta\Omega_{m-1}' = \left[\sin\Delta\theta \cos\Delta\theta + \frac{\sin\left(\frac{\Delta\phi}{4}\right)\cos\left(\frac{\Delta\phi}{4}\right)}{8}\right] \Delta\theta\, \Delta\phi$$

and

$$m = \frac{\pi}{2\,\Delta\theta}, \qquad n = \frac{2\pi}{\Delta\phi} - 1$$

$$i = 0, 1, \cdots, m \qquad j = 0, 1, \cdots, n$$

$$\theta_i = i\,\Delta\theta \qquad \phi_j = j\,\Delta\phi$$

The preceding equation (2) may be used for either $H(z, -)$ or $H(z, +)$. Figure 3 shows the geometrical arrangement and identifies centroid values of radiance for $H(z, -)$. To use (2) for the determination of $H(z, +)$, reflect the sphere in its equatorial plane.

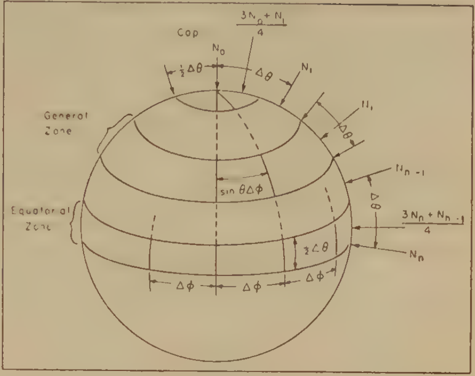

FIG. 3—Spherical grid used to perform the numerical integration to obtain irradiance and spherical irradiance. For simplicity, only three general zones are shown.

Computation of $h(z, -)$ *and* $h(z, +)$ *from* $N(z, \theta, \phi)$—The procedure for obtaining scalar irradiance from radiance distribution data is expressed by

$$h(z, \pm) = \int_{\pm} N(z, \theta, \phi)\, d\Omega \qquad (3)$$

The mechanics of numerical integration to obtain hemispherical scalar irradiance, $h(z, -)$, $h(z, +)$, are expressed in (4) in which the same general notation is employed as in (2) and Figure 3 and is used in the same general manner.

$$h_{(\text{hemispherical})} = \sum_{i=0}^{m} \sum_{j=0}^{n} N_{ij}\, \Delta\Omega_i \qquad (4)$$

where

$$N_{0,j} = N_{0,0}$$

and where the $\Delta\Omega_i$ are weighted solid angles defined for the indicated zones ($i = 0, 1, \cdots, m$) as follows

$$\Delta\Omega_i = \sin\theta_i\, \Delta\theta\, \Delta\phi, \qquad \text{for} \quad i = 2, 3, \cdots, m-2$$

$$\Delta\Omega_0 = \tfrac{3}{8} \sin\left(\frac{\Delta\theta}{4}\right) \Delta\theta\, \Delta\phi$$

$$\Delta\Omega_1 = \left[\sin\Delta\theta + \frac{\sin\left(\frac{\Delta\theta}{4}\right)}{8}\right] \Delta\theta\, \Delta\phi$$

$$\Delta\Omega_{m-1} = \left[\cos\Delta\theta + \frac{\cos\left(\frac{\Delta\theta}{4}\right)}{8}\right] \Delta\theta\, \Delta\phi$$

$$\Delta\Omega_m = \tfrac{3}{8} \cos\left(\frac{\Delta\theta}{4}\right) \Delta\theta\, \Delta\phi$$

In the numerical evaluation of (2) and (4) each hemisphere was divided into 8 increments of $\Delta\theta$ and 2 increments of $\Delta\theta/2$ and into 18 increments of $\Delta\phi$. Substituting the values of

$$\Delta\theta = \pi/2m = 10^{\circ} = 0.1745 \quad \text{radians}$$

$$\Delta\phi = \pi/n = 20^{\circ} = 0.3491 \quad \text{radians}$$

into (2) and (4) a table of factors, $\Delta\Omega$ and $\Delta\Omega'$ was obtained (Table 1).

Table 1—*Summation factors for computation of irradiance and scalar irradiance*

θ_i (degrees)		$\Delta\Omega_i$	$\Delta\Omega_i'$
0 and	180	0.000 966	0.000 966
10	170	0.010 918	0.010 747
20	160	0.020 835	0.019 579
30	150	0.030 461	0.026 379
40	140	0.039 160	0.029 997
50	130	0.046 665	0.029 997
60	120	0.052 758	0.026 379
70	110	0.057 247	0.019 579
80	100	0.067 603	0.010 747
90	90	0.022 824	0.000 996

For each hemisphere the sum of the 18 values of N_{ij} for each i was multiplied by the corresponding $\Delta\Omega_i'$ or $\Delta\Omega_i$, and the sum of the results gave the irradiance or scalar irradiance, respectively, for the hemisphere.

Computation of optical properties—In modern two-flow theory the functions which describe the interaction of light with water must, in general, be associated with the specific stream to which they apply [*Preisendorfer*, 1958a]. For horizontally stratified scattering-absorbing media (for example, large bodies of water), there will be one set of functions for the downwelling stream (identified by the symbol $-$) and another set of functions for the upwelling stream (identified by the symbol $+$). The functions which have been computed in this experiment from the radiance distribution are shown in Table 2.

Computation of $K(z, -)$ *and* $K(z, +)$—The attenuation functions, $K(z, -)$ and $K(z, +)$ for natural downwelling and upwelling light in the water are determined by the equation

$$K(z, \pm) = \frac{\ln \dfrac{H(z - \Delta z/2, \pm)}{H(z + \Delta z/2, \pm)}}{\Delta z} \qquad (5)$$

Table 2—*Optical properties associated with water*

Item	Downwelling	Upwelling
Attenuation functions	$K(z, -)$	$K(z, +)$
Volume absorption functions	$a(z)$	$a(z)$
Reflectances of a hypothetical horizontal plane	$R(z, -)$	$\left\{\begin{array}{l}R(z, +) = \\ \quad 1/R(z, -)\end{array}\right.$
Distribution functions	$D(z, -)$	$D(z, +)$

This equation (5) is derived from the precise definition of $K(z, \pm)$,

$$H(z, \pm) = H(0, \pm) \cdot \exp\left[-\int_0^z K(z', \pm)\, dz'\right]$$

where the primed symbols denote dummy variables of integration. Because the measurement of $H(0, \pm)$ is difficult, the definition of $K(Z, \pm)$ can be restated for a depth difference Δz

$$H\left(z + \frac{\Delta z}{2}, \pm\right) = H\left(z - \frac{\Delta z}{2}, \pm\right) \cdot \exp\left[-\int_{z-\Delta z}^{z+\Delta z} K(z', \pm)\, dz'\right]$$

If Δz is sufficiently small, $K(z, \pm)$ may be treated as being constant over the intervals $z - \Delta z/2$, $z + \Delta z/2$ and

$$\int_{z-\Delta z/2}^{z+\Delta z/2} K(z', \pm)\, dz' = K(z, \pm) \int_{z-\Delta z/2}^{z+\Delta z/2} dz'$$

$$= K(z, \pm)\, \Delta z = \ln \left[\frac{H\left(z - \dfrac{\Delta z}{2}, \pm\right)}{H\left(z + \dfrac{\Delta z}{2}, \pm\right)}\right]$$

The attenuation functions $K(z, \pm)$ generally vary with depth. Their values at any given depth z are determined by the operational procedure summarized in (5), which requires knowledge of the irradiances just above and just below z.

Computation of $R(z, -)$—The reflectance $R(z, -)$ of a hypothetical horizontal plane in water with respect to the downwelling flux at a depth z below the surface was computed from the defining equation

$$R(z, -) = \frac{H(z, +)}{H(z, -)} \tag{6}$$

Note that

$$R(z, +) = \frac{H(z, -)}{H(z, +)}$$

Computation of distribution functions—Distribution functions $D(z, \pm)$ are measures of the directional distribution of the upwelling and downwelling radiance. They are defined [*Preisendorfer*, 1958a] by the equations

$$D(z, \pm) = \frac{h(z, \pm)}{H(z, \pm)} \tag{7}$$

Computation of the absorption function—The value of the absorption function $a(z)$ was determined from the equation

$$a(z) = \frac{\ln\left[\dfrac{\overline{H}\left(z - \dfrac{\Delta z}{2}, +\right)}{\overline{H}\left(z + \dfrac{\Delta z}{2}, +\right)}\right]\overline{H}(z, +)}{\Delta z\, h(z)} \tag{8}$$

where $\overline{H}(z, +) = H(z, +) - H(z, -)$, net upwelling irradiance, and $h(z) = h(z, +) + h(z, -)$, the scalar irradiance. Equation (8) is developed as follows. The operational definition of the absorption function $a(z)$ is

$$a(z) = \frac{1}{h(z)} \times \frac{d\overline{H}(z, +)}{dz} \tag{9}$$

[*Preisendorfer*, 1957]

Now, by definition of $\overline{K}(z)$, we have

$$\frac{d\overline{H}(z, +)}{dz} = -\overline{H}(z, +)\overline{K}(z) \tag{10}$$

and

$$\overline{H}(z, +) = \overline{H}(0, +) \cdot \exp\left[-\int_0^z \overline{K}(z')\, dz'\right]$$

Furthermore, between the two depths, $z - \Delta z/2$, $z + \Delta z/2$, we have by definition of $\overline{K}(z)$

$$\overline{H}\left(z + \frac{\Delta z}{2}, +\right) = \overline{H}\left(z - \frac{\Delta z}{2}, +\right) \cdot \exp\left[-\int_{z-\Delta z/2}^{z+\Delta z/2} \overline{K}(z')\, dz'\right] \tag{11}$$

$\overline{K}(z)$ may be considered constant over the interval $z - \Delta z/2$, $z + \Delta z/2$ when Δz is sufficiently small. Therefore, from (11)

$$\int_{z-\Delta z/2}^{z+\Delta z/2} \overline{K}(z')\, dz' = \overline{K}(z) \int_{z-\Delta z/2}^{z+\Delta z/2} dz'$$

$$= \overline{K}(z)\, \Delta z = \ln\left[\frac{\overline{H}\left(z - \dfrac{\Delta z}{2}, +\right)}{\overline{H}\left(z + \dfrac{\Delta z}{2}, +\right)}\right] \tag{12}$$

Substituting in (9) the values of $d\overline{H}/dz$ as given in (10) and $\overline{K}(z)$ as given in (12), we have the convenient operational equation (8) for $a(z)$.

Other physical measurements—In addition to the radiance distribution measurements described above, it was possible to measure some of the water properties by direct methods. The function $K(z, -)$ was obtained by direct measurement with a flat-plate collector used to obtain relative values of $H(z, -)$ at various depths. The collecting surface of this instrument (Figure 4) is carefully designed to collect radiant flux in accordance with the law

$$P(\theta) = P(0) \cos \theta \tag{13}$$

that is, the surface is a Lambert collector.

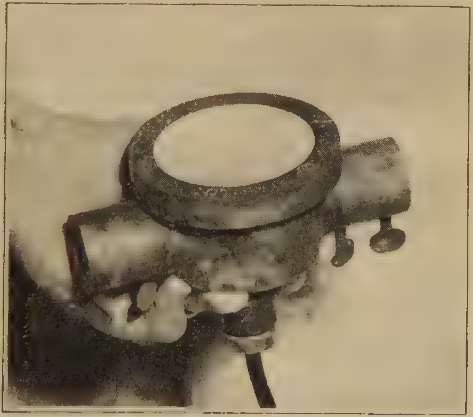

Fig. 4—Flat-plate Lambert collector for measuring relative values of irradiance

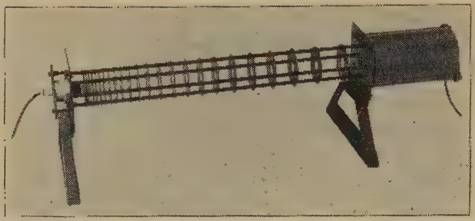

FIG. 5—Hydrophotometer for measuring the total attenuation coefficient

The volume attenuation function α was measured with a hydrophotometer (Fig. 5). The length of the path of the transmitted beam is $r = 1$ meter. This instrument is designed to be insensitive to changes in coupling (between the radiant flux and the detector) when the index of refraction of the medium changes over a wide range. It is also designed to minimize the effect of forward scattered light within the beam. Recent work by *Preisendorfer* [1958b] makes it possible to predict that the error created by forward scattered light within the beam of this instrument will be of the order of 0.3 per cent in the value of α.

Results—The experimental values obtained at a depth of 29 meters for eight optical properties of Lake Pend Oreille are given in Table 3. The total scattering coefficient for collimated light s can be found from a and α by

$$\alpha(z) = a(z) + s(z) \qquad (14)$$

This table includes this calculated value of s and also the directly measured value of $K(z, -)$ for $z = 29$ meters.

TABLE 3—*The optical properties of Lake Pend Oreille at depth 29 meters and for a wavelength band 64mμ wide (half-band width) peaking at 480 mμ*

Property	April 28, 1957 Computed from $N(29, \theta, \phi)$	March 16, 1957 Measured directly	Calculated indirectly
$K(29, -)$	0.169/m	0.184/m	
$K(29, +)$	0.164/m		
$R(29, -)$	0.0227		
$D(29, -)$	1.31		
$D(29, +)$	2.78		
$a(29)$	0.117/m		
$\alpha(29)$		0.442/m	
$s(29)$			0.325

Discussion—These measurements were carried out in the spring of 1957 before the start of the spring plankton bloom and well before the development of any thermocline. The lake was tested extensively to determine its homogeneity and was found to be very nearly homogeneous by every test. Therefore the values of $\alpha(29)$ and $a(29)$ and $s(29)$ are representative values for all depths below 5 meters. The values of the properties given here should approach the minimum values for the year. The values $K(z, -)$, $K(z, +)$, $R(z, -)$, $a(z)$, $s(z)$ would be expected to rise in the upper layers of water during the plankton bloom and would probably be higher for all depths during the heavy spring run-off.

All of the constants reported here are associated with a half bandwidth of 64 mμ wide centered at 480 mμ.

In Table 3 the value of $K(29, -)$, measured directly, was obtained under overcast lighting conditions in March, whereas the value computed from $N(29, \theta, \phi)$ is for clear sunny conditions in April. These conditions may account for the difference in the two tabulated values of $K(29, -)$.

Table 4 gives relative values of irradiance and scalar irradiance as obtained by the integration procedure. The array of properties for this range of depths may be readily computed from the tabular values.

TABLE 4—*Integrated relative values of irradiance and scalar irradiance*

z(meters)	$H(z, -)$	$H(z, +)$	$h(z, -)$	$h(z, +)$
4.24	721,000	15,500	899,000	41,900
10.42	329,000	6,040	413,000	16,500
16.58	109,000	2,230	141,000	6,190
28.96	13,100	298	17,200	830
41.30	1,660	39.0	2,190	108
53.71	221	5.19	289	14.3

One of the prime objectives of making these measurements was to provide numbers which could be used to confirm certain theoretical relationships which relate the various optical properties. For example, it has been shown [*Preisendorfer*, 1958a] that in general

$$K(z, -) - R(z, -)K(z, +)$$
$$= a(z)[D(z, +)R(z, -) + D(z, -)]$$

If the values for April 28 (column 2 of Table 3) are substituted in this expression the result is

$$.165 \sim .161.$$

REFERENCES

DUNTLEY, S. Q., R. J. UHL, R. W. AUSTIN, A. R. BOILEAU, AND J. E. TYLER, An underwater photometer, *J. Opt. Soc. Am;* **45**, 904 (abstr.), 1955.

PREISENDORFER, R. W., Divergence of the light field in optical media, *Scripps Inst. Oceanog., Univ. Calif., Ref. 58-41,* 16 pp., 1957.

PREISENDORFER, R. W., Directly observable quantities for light fields in natural hydrosols, *Scripps Inst. Oceanog., Univ. Calif., Ref. 58-46,* 29 pp., 1958a.

PREISENDORFER, R. W., A General theory of perturbed light fields, with applications to forward scattering effects in beam transmittance measurements, *Scripps Inst. Oceanog., Univ. Calif., Ref. 58-37,* 22 pp., 1958b.

TYLER, J. E., Radiance distribution as a function of depth in the submarine environment, *Scripps Inst. Oceanog., Univ. Calif., Ref. 58-25,* 1958.

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SVANTE ARRHENIUS' CONTRIBUTION TO EARTH SCIENCE AND COSMOLOGY

BY

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Svante Arrhenius' great interest in the physics and chemistry of the earth and the universe developed early in his student years, and continued throughout his life. Comprehensive presentations of his views on related problems were included in his *Lehrbuch der Kosmischen Physik* (1903), and in a more popular form in *Världarnas Utveckling* (Worlds in the Making). His contributions to earth science and cosmology occur in 52 papers, distributed between 1883 and 1919, and listed in the bibliography below.

In relatively few cases did Arrhenius carry out experimental research in these fields. His contribution consists mostly in the application of physical and chemical theory to existing astronomical, geophysical and geological observations in an attempt to integrate the information into a consistent and quantitatively understood natural system.

Careful descriptive work may retain its validity if not also its interest, whereas theoretical explanations of poorly known natural systems display a high mortality rate when confronted with accumulating evidence. Accordingly, some of Arrhenius' geophysical and geochemical ideas appear today to have been of importance only as catalysts of development, finally leading into other directions. Others have been rejected as inadequate in the light of present evidence, and others again still enjoy popularity, in some cases after decades of relegation into improbability.

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Astrophysics and cosmology

The structure and development of galaxies and stars attracted Arrhenius' special interest as a basis for an integrated cosmogonic hypothesis. From the observed speed of rotation of two assumed hydrogen clouds around the central body of the double star Mira Ceti, he computed the mass of this central body. He critically examined the early measurements of internal motion of the arms of the spiral galaxy Messier 101, and demonstrated that the assumed motion would lead to a complete degradation of the spiral structure in a time much shorter than a reasonable average lifetime of spiral galaxies as estimated by their abundance.

By a comparison between the Milky Way as seen from our solar system and the spiral galaxy Messier 51 as it would appear, seen from a point inside it and about halfway from the center, he drew attention to the striking similarity and suggested that our galaxy is of the spiral type.

From observations on the gaseous nebulae and the characteristic dynamics of our solar system he tried to derive a plausible scheme for the development of such systems from original immense clouds of rarefied gas and dust. For this purpose he adopted the main features of the hypothesis originally suggested by Descartes, Swedenborg and Kant and extensively modified into a physically more acceptable form by Laplace. It was realized in the beginning of this century that there are two fatal objections to the hypothesis as formulated by Laplace; the insufficient centrifugal force at the equator of the proto-sun for throwing off the rings, which Laplace assumed as protoplanets, and the stability of such rings, once they were formed, which would prevent the accretion of their matter into planets. To overcome this difficulty Chamberlin (1901) and Moulton (1905) revived another type of hypothesis, originally suggested by Buffon, and involving the catastrophic interaction between the sun and another star. Arrhenius, however, who preferred a monistic hypothesis, suggested that the solar system in an early state consisted of a rotating proto-sun with a central body surrounded by a large mass of gas. Around this mass, large, captured condensation centers were moving, also surrounded by gas masses. Due to the large dissipation of energy between the gas masses moving far from the fundamental plane, these were gradually concentrated in the plane of the ecliptic of the proto-sun, and angular momentum was transferred from this to the protoplanets which resulted in a decrease in the speed of solar rotation, and an increase in the time of revolution of the planets, and consequently a readjustment of these into the present larger orbits. A new explanation was thus suggested for the fact that the planets all move in approximately circular orbits, approximately in the plane of the ecliptic and in the same sense of rotation as the sun. Deviations from this rule in the peripheral parts of the solar system were explained by Arrhenius as due to the original low density of matter in these parts, preventing a complete change from the original state of motion of the captured protoplanets to final equilibrium with the motion of the sun. This view was supported by the similar characteristics of the short period comets. As a means for the primary aggregation of dust into larger bodies with a gravitational field, strong enough to carry on the process, Arrhenius suggested capillary forces acting on the surfaces, especially in connection with wetting by liquid gas condensates.

A controversial issue of the time was the question of the cooling rate of the sun, and the age of the solar system. The classical calculations by Helmholtz, modified by Lord Kelvin, indicated that the sun could not be older than about 15 million years. This was in obvious disagreement with geological evidence and furthermore, to Arrhenius it appeared to be contradictory to his cosmogonic ideas, based on a steady state universe. He consequently felt it necessary to search for a mechanism that could supply the energy needed, and claimed that on the basis of existing knowledge, it would be reasonable to assume that the free energy change of processes increases with temperature, and that exothermic reactions in the interior of the stars would thus yield energies of a magnitude far above those measured in chemical reactions on the earth. Paradoxically enough, the discovery of radioactivity brought this hypothesis into temporary disrepute; it was first hoped that the radioelements discovered in the Earth's crust would represent the solar fuel. A search for the thorium and uranium series elements in the sun's spectrum, however, revealed the lack of sufficient amounts. When finally Rutherford suggested the loss of mass accompanying fusion of hydrogen into helium as the source of energy in stars, this mechanism was at the time also considered insufficient, due to drastic underestimates of the amount of hydrogen present in the sun.

A basic feature of the universe, as thought of by Arrhenius, was its infinity in time; there was no beginning and no end. He held this view as he found no other way out of the paradox that he and his contemporaries saw in the application of the first and second laws of thermodynamics to the universe. Clausius had stated that the energy of the world is constant and the entropy of the world approaches a maximum. If, however, the universe had been in existence for an infinite length of time, the maximum entropy would have been achieved; all heat would have died away. If, on the other hand, to satisfy the entropy law, the universe were assumed to have a finite lifetime, the creation of energy at some time would be required, and this would violate the first law of thermodynamics constituting the first part of Clausius' statement. As this at the time appeared to be one of the most profound laws of nature, the search was directed toward permitted violations of the second law. Arrhenius pointed out that a stellar condensation mechanism would provide the necessary perpeteuum mobile of the second kind, without employing a Maxwellian demon. The energy radiated into space by cooling stars would largely be received and stored at near-zero temperature by the adiabatically expanding gas nebulae. Due to their small gravitational field, the escape velocity of the constituent gases would be small. The most rapidly moving molecules, carrying a major part of the heat, would in this way be selectively removed, later to be trapped by the strong gravitational field of the intranebular stars. Heat would thus be continuously streaming over from the cold nebulae to the hot stars, decreasing the entropy of the system.

Arrhenius' theory attracted a great deal of interest. Poincaré in his contribution to the discussion expressed the opinion that although it was obvious that the suggested mechanism could tremendously increase the lifetime of the universe, it was not clear whether it could provide the infinite existence desired. Arrhenius for this reason continued his search for entropy decreasing mechanisms. He pointed out that for maximum entropy to obtain in the universe, all motion had to be equalized, as the generation of heat through collision would upset the equilibrium. Astronomical observation, however, strongly indicated that galactic motion is far from uniform, and the fact that the speed appeared to increase with distance, safeguarded the concentration of energy by collision for unlimited time.

The principle of infinity in time thus appeared to be conserved and it was natural for Arrhenius to deal with other cosmological problems on this basis. One of those, which attracted his interest, was the question of the origin of life. His contemporaries among geologists and biologists generally favored the Aristotelean idea of spontaneous generation during an early stage of the history of the Earth, extrapolating back from the evidence of evolution. Arrhenius, however, starting from the concept of infinity of time, did not have any need for a hypothesis involving a singular event like the creation of life. Still it was necessary to find means for particles of living matter to travel through space. The idea of panspermism goes back to the Pythagorean school, but more definite statements regarding the mechanism of transport were not formulated until the 19th century, when meteorites were proposed as vehicles for primitive organisms, and the carbon of meteorites was supposed to be of organic origin.

Arrhenius suggested that radiation pressure might be the driving force in transporting through space "spores" of living matter which had to have a size of the order of the wave length of light, to be able to escape from a solar system and to travel relatively rapidly through space. The discovery toward the end of the century of manifestations of submicroscopic living organisms confirmed that life extended down to the small particle-size required. Later on, in 1901, experimental proof of radiation pressure was furnished by Lebedev and by Nichols and Hull, and Arrhenius felt encouraged to elaborate further on his panspermic hypothesis. The critical questions concerned the survival of living matter after exposure during thousands or ten thousands of years to low temperature and radiation in space. Arrhenius took a vivid interest in the investigation of these questions, and induced several of his colleagues in different countries to carry out physiological

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experiments to resolve the problems. Applying his equation for the rate of reaction, he indicated that the metabolic processes would slow down approximately 2.5 times for each decrease of temperature by 10°C, and predicted that the low extraterrestrial temperatures would have a preserving effect on living organisms.

Important criticism of the hypothesis came from Becquerel, who after investigation of the influence of artificial ultraviolet radiation on spores, concluded that living matter could not survive exposure to ultraviolet and possible corpuscular radiation. His objections were, however, left without the attention they deserved, due to the lack of knowledge of the true intensity and character of radiation outside the Earth's atmosphere.

The development of relativistic physics that took place during the decades following upon Arrhenius' formulation of his cosmological ideas, changed basically the approach to astrophysical questions, and his concept of the universe as a perpetuum mobile is merely of historical interest. The problems of the time structure of the universe, its possible reversibility, and the status of the second law in an oscillating relativistic universe, although now discussed in a more sophisticated way, are, however, still far from their solution.

The hypothesis of spontaneous generation appears today to have taken over the field from the panspermic hypothesis. The general importance of radiation pressure in stellar interiors and in the condensation of stars from the interstellar gas, is, however, still acknowledged, although electric and magnetic fields have been found also to be important accelerators of atoms and electrons in space. The problems of how the galaxies can maintain their spiral structure in spite of rapid motion is still occupying the minds of astrophysicists. A general solution now fashionable is a finite time scale for the galaxies.

Arrhenius' modification of Laplace's concept of the origin of the solar system was overshadowed by Chamberlin's and Moulton's star encounter hypothesis, and others of similar type that followed during the next three decades. In the early 40's, however, Alfvéns' and v. Weizsäcker's works returned the interest to monistic schemes for the explanation of the origin and evolution of the solar system, and such hypotheses today appear again to dominate

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cosmophysical and cosmochemical thinking. Alfvéns' approach is original insofar as he ascribes decisive operative importance to magnetohydrodynamic and electrostatic forces. v. Weizsäcker revived Arrhenius' scheme and to a large extent incorporated it into his more elaborate hypothesis, later modified by Kuiper and by Urey. Especially Urey's work has emphasized the probability of a low-temperature development of the planets.

Volcanism and tectonics

In the interpretation of volcanic activity Arrhenius saw a possibility for a successful application of physico-chemical principles to natural phenomena. As active volcanism today is largely concentrated to coastal regions, and as volcanic eruptions are accompanied by the release of large amounts of gases, principally water vapor, the prevalent belief of the time was that ocean water penetrates to or into magma, and in some way causes the eruption. The processes envisioned appeared to Arrhenius to be physically unsound, and he suggested a mechanism based on the known or extrapolated behavior of water at elevated temperatures and pressures. The main point to be explained was how water could stream into a melt against a pressure head corresponding to the lava column from the top of the volcano down to the sea level. Arrhenius pointed out the increasing ionic dissociation of water with temperature, which would at a few hundred degrees make water a stronger acid than silicic acid. At the temperatures of magma the hydroxyl ions of water would thus combine with the cations of silicates, setting free silicic acid. It was assumed that the rocks underlying the ocean floor and separating the magma from the sea water, had a porosity high enough to permit a slow flux of water, through cooler parts as liquid and through the heated wall of the magma basin in the form of supercritical steam. The steam in the fissures, fractures or pores in immediate contact with the magma would rapidly dissolve. Equilibrium would be prevented by convection within the magma basin, and a unidirectional flow of water into the melt would be maintained. The viscosity and density of the melt would be lowered by the uptake of water, and the expansion would force the magma to rise up through the volcanic pipe. At cooling in this region, the reaction mentioned above would be reversed, silicic acid would react with the hydrates, and water would be set free, causing a volcanic eruption by explosive boiling. The increased pressure head in the magma basin would not be able to stop the flow of water, as the pores of the rock are too small to permit the viscous silicate melt to enter. The system would thus be an analog to an osmotic cell, the semipermeable membrane corresponding to the porous rock, and the osmotic pressure to the weight of the lava column extending above sea level.

In the light of later experimental work the hypothetical reaction between the molten silicate and water does not appear tenable; the solubility of water is found to increase with decreasing temperature of the melt, and the final expulsion of water is now known to be associated with crystallization. The theory of the osmotic cell analog, however, is today still accepted[2] and has been subject to an experimental study by Goranson[3] confirming Arrhenius' estimate of the order of magnitude of differential pressure.

Volcanologists have to a large extent abandoned the idea of surface waters as a general cause of volcanism, and more emphasis has been laid on the importance of juvenile water, buried in the interior of the planet at the creation of the solar system, dissolved in magma, and brought to the surface for the first time by volcanic eruption. Although it may be too early to predict a renaissence of surface water into its previous role in volcanology, it is interesting to note that the last few years' search in hot springs and volcanoes for juvenile water as defined by its hydrogen and oxygen isotope composition, has so far failed; the steam and water in all cases investigated bear the marks of the local surface water.[4]

The close connection with van t'Hoff in his physico-chemical work, drew Arrhenius' attention to the interesting features of the natural salt deposits, and he became particularly interested in the physics of the peculiar intrusions known as salt domes. He attempted to explain the intrusion process as a gravitational rearrangement of the unstable stratification of clastic sediments with a relatively high density on top of the low density salt deposits. This explanation today remains the one most generally accepted.[5]

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[2] Cf. Barth, T. W., 1952, Theoretical Petrology. Wiley.

[3] Goranson, R. W., 1937, Silicate water systems: The "osmotic pressure" of silicate melts. Am. Mineral. *22*, 485.

[4] Craig, H., Boato, G., and White, D., 1956, NAS-NRC Publication 400, 29–38.

Physics and chemistry of the planetary atmospheres

Toward the end of the nineteenth century observations became available on the composition of the atmospheres of the planets in our solar system. Arrhenius realized that the variation in atmospheric composition from one planet to another could be correlated with parameters such as gravitational field and surface temperature of the planet, and that important conclusions regarding the development of the earth and the other planets could be drawn from the present atmospheric composition. Beside the introduction of this general principle he made two specific contributions to the physical chemistry of the atmosphere. One was the computation of the effect of atmospheric carbon dioxide on the planetary heat budget; the other was the suggestion of photodissociation as a source of atmospheric oxygen.

The Belgian scientist Koene in 1856 drew the attention to the fact that the amount of oxygen in the Earth's atmosphere appears to be roughly equivalent with the amount of fossil organic carbon in the crust, and that one of the main components of the primitive atmosphere probably was carbon dioxide, which has during geologic time gradually been transformed to organic matter and oxygen by the photosynthetic action of plants. This hypothesis, which is still generally accepted, was included as sufficient explanation in Arrhenius' textbook on cosmic physics in 1903. In his paper on the atmospheres of the planets of 1910 he expresses, however, the view that part of the oxygen must have been furnished by photodissociation of water and carbon dioxide in the highest layers of the atmosphere, and that the oxygen produced entered into reactions with the reduced silicates of the crustal rocks and with hydrocarbons and hydrogen, which he assumed to be main components of the primordial atmosphere together with nitrogen. The original reducing atmosphere was thus gradually changed to contain mainly nitrogen, oxygen and argon, and photodissociation of carbon dioxide in plants became possible after the removal by oxidation of poisonous compounds, such as carbon monoxide, hydrogen sulphide, and cyanides. Although a steady production of oxygen by photolysis of carbon dioxide hardly is considered possible today, and as carbon dioxide would not exist in thermodynamic equilibrium in a reducing atmosphere, as shown by Urey,[6] the dissociation of water vapor into oxygen and hydrogen is a mechanism considered by many workers as operative in the evolution of the atmosphere, especially as the subsequent escape of hydrogen to outer space makes possible a continuous net production of oxygen.[7]

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[5] SCHEIDEGGER, A., 1958, Principles of Geodynamics. Springer.

Arrhenius' great interest in the evolution of the stars and the planets led him to extensive studies of the heat budget of the Earth. His ideas on the heat flux from the interior of the Earth stemmed from the era of Lord Kelvin, and thus are but of historical interest today. During the later part of his life Arrhenius witnessed the discovery of the role of radioactivity in geothermal processes and recognized its decisive importance, as is evident from the later editions of his "Worlds in the Making". However, he did not attempt to compute the flux of radiogenic heat, probably due to the lack of adequate geochemical data up to World War I, which marks the end of his creative period in the earth sciences. His important contribution lies in the consideration of the factors regulating the exchange of heat between planetary surfaces and outer space. The insulating effect of the atmospheric gases and the relation of this effect to the dynamics of exchange with the lithosphere, the hydrosphere and the biosphere presented to him a challenging problem which kept his active interest from 1895, when it is mentioned for the first time in a letter to Wilhelm Ostwald, to the end of his life. This may explain why the development of the "greenhouse theory" is widely attributed to Arrhenius in spite of the fact that it had been suggested in principle already by Fourier, and further developed by Pouillet and Tyndall. Arrhenius' contribution to the problem may be expressed in the words of T. C. Chamberlin,[8] "Dr. Arrhenius has taken a great step in advance of his predecessors in reducing his conclusions to definite quantitative terms, deduced from observational data". Tyndall's experiments on the absorption of heat in gases were carried out with temperatures of the radiating body between 1600 and 100°C. Arrhenius extended these experiments to 15°C, the effective radiate temperature of the Earth, and from his results computed the fraction of the Earth's radiation absorbed by atmospheric carbon dioxide. To establish the total effect of carbon dioxide and water vapor in a real atmosphere he used Langley's observations of the amount of heat received from the full moon at different heights above the horizon, correcting for the higher effective temperature of the moon's surface, which he determined both theoretically and, in good agreement, from radiation measurements by Very. He further proceeded to compute the change in temperature of the Earth's surface as a function of changes in the carbon dioxide content of the atmosphere, and the positive feedback effect due to the variation of the water vapor content of the air with temperature. The conclusion was that, neglecting the considerable effect of water vapor, a change of concentration by a factor of two of the carbon dioxide content of the atmosphere would bring about a change of the average temperature change by at least 4°C. A decrease in CO_2 would further increase the temperature gradients over the surface of the Earth, and vice versa. The secondary effect, caused by the temperature dependent change in water vapor content of the atmosphere, would amplify the primary one with at least a factor of two. Arrhenius thus considered it a possible hypothesis that the changes in climate, recorded in the geological column, were caused by changes in the amount of CO_2 in the Earth's atmosphere. After reviewing the essential details of the carbon cycle, which were already well known at this time, he concluded that any increase in the carbon dioxide content of the air would be counteracted by an immediate expansion of the plant biomass[9] and by the buffering action of the ocean, and over a period of time of the order 10^4 years by carbonatisation of silicates. In view of the instability of the system, however, he considered changes in the atmospheric CO_2 content possible, with a magnitude and duration sufficient to induce amplifying side effects like changes in water vapor content of the atmosphere and in albedo of the Earth's surface and ultimately leading to changes in the mean temperature of several degrees Celsius. As reasons for increased transfer of CO_2 to the atmosphere he pointed out increased volcanic activity, shrinkage of the oceanic reservoir or, in recent times, the consumption of fossil fuel.

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[6] UREY, H. C., 1952, The Planets, their Origin and Development. Yale Univ. Press.

[7] GOLDSCHMIDT, V. M., 1933, Fortschr. Min. Krist. Petr. *17*, 112; POOLE, J., 1941, Proc. Roy. Soc., Dublin, *22*, 345; HARTECK, P., and JENSEN, J., 1948, Z. Naturforschung 3 a, 591; UREY, op. cit.

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[8] 1899, J. Geol. *7*, 547.

[9] This idea has recently been revived, and approached quantitatively, by Eriksson and Welander, Tellus *8*, 155–175.

The carbon dioxide theory for several decades enjoyed great popularity among the earth scientists, and attempts were made to find confirming evidence in the geological record, and to trace the secular rise in atmospheric CO_2 due to combustion of fossil fuels.[1] However, it fell into temporary disrepute mainly due to indications that the thermal effect of atmospheric CO_2 would be lower than previously believed, and due to the lack of knowledge of the rate of transfer of atmospheric CO_2 into the ocean. Modern work on the dynamics of the cycle of carbon dioxide, employing the natural radioactive isotope C^{14} as a tracer, has, however, reinstated the theory as a possible working hypothesis,[2] and renewed attention has been drawn to the importance of instability in the system, making self-sustained oscillations possible.[3] New data by Elsasser (unpubl.) on the absorption spectrum of carbon dioxide, water vapor and ozone promise a more precise evaluation of the triggering thermal effect. The largest uncertainty at the present time appears to rest with the relative importance and interplay of feedback effects in nature. At least an empirical solution of these problems appears to lie within the limits of possibility. It is hoped that part of the necessary experimental data will be furnished by precision inventories of the carbon reservoirs undertaken during the International Geophysical Year 1957–58.

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[1] CALLENDAR, G. S., 1938, Quart. J. Roy. Met. Soc. *64,* 223; 1940, Ibid. *66,* 395; 1949, Weather *4,* 310.

[2] BUCH, K., 1933, Rapp. Cons. Explor. Mer, *85,* 71; REVELLE, R., and SUESS, H., 1957, Tellus *9,* 18–27; ARNOLD, J., and ANDERSON, E., 1957, Ibid.; CRAIG, H., 1957, Ibid.

[3] PLASS, G. N., 1956, Tellus *8,* 140; ERIKSSON, E., and WELANDER, P., op. cit.

New possibilities are also opened for tracing the dependence of climatic oscillations on atmospheric filter effects in the past geological history of the Earth. Long period variations in the specific carbon activity of the air by two per cent or more in historic time have thus recently been demonstrated.[4]

Arrhenius' achievements in the exact sciences stemmed largely from his lack of respect for the artificial but traditionally upheld boundaries between physics and chemistry. The creation of the new science of physical chemistry may thus be regarded as an event of at least as great general importance as the launching of pioneer contributions in this field, such as the theories of reaction kinetics and ionic dissociation.

Similar conclusions appear to be justified when Arrhenius' contributions to earth science and cosmology are regarded in retrospect. Some of his theories still stand today, others have fallen. The most important consequence of his work, however, appears to be the increased stimulus to tearing down the borders between chemistry and astronomy, and between geology and the exact sciences. This achievement, together with his successful results and his catalyzing failures made him one of the founders of modern earth science and cosmology.

Svante Arrhenius' publications in earth science and cosmology[5, 6]

Iakttagelser rörande klotblixt. (Öfversigt 1883, *7,* 77.)
Über den Einfluss der Sonnenstrahlen auf die elektrischen Erscheinungen in der Erdatmosphäre. (Meteorol. Zeitschr., *5,* 297, 348, 1888.)
Über den Einfluss des Mondes auf den elektrischen Zustand der Erde. (Bihang. *20,* Afd. 1, No. 6, p. 41, 1895.) (With N. Ekholm.)
Über den Einfluss des atmosphärischen Kohlensäuregehalts auf die Temperatur der Erdoberfläche. (Bihang. *22,* Afd. 1, No. 1, p. 102, 1896.)
On the influence of carbonic acid in the air upon the temperature of the ground. (Phil. Mag. *41,* 237.)
Naturens värmehushållning. (Nordisk Tidskrift 1896, p. 121.)

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[4] De Vries, H., 1958, Proc. Koninkl. Nederl. Akad. Wet., Ser. B, *61,* No. 2.

[5] Works published between 1883 and 1919 are quoted from the list of publications given by O. Arrhenius in Medd. 5, 1–11, 1919.

[6] Bihang = Bihang till Kungl. Vetenskapsakademiens Handlingar.
Öfversigt = Öfversigt af Kungl. Vetenskapsakademiens Förhandlingar.
Medd. = Meddelanden från Kungl. Vetenskaps-Akademiens Nobelinstitut.

Über den Einfluss des Mondes auf die Polarlichter und die Gewitter. (Handlingar, *31,* No. 2, p. 77, 1898.) (With N. Ekholm.)

Über die nahezu 26-tägige Periode der Polarlichter und der Gewitter. (Handlingar, *31,* No. 3, p. 45, 1898.) (With N. Ekholm.)

Die Einwirkung kosmischer Einflusse auf die physiologischen Verhältnisse. (Skandinavisches Archiv f. Physiologie, *8,* 367, 1898.)

Les oscillations séculaires de la temperature. (Revue générale des sciences 1899, p. 22.)

Om ljudets förmåga att tränga in i vatten från luft. (Lotsstyrelsens berättelse 1898, Sthlm 1899, p. 4.)

Über die Ursache der Nordlichter. (Öfversigt 1900, p. 545, Physikalische Zeitschr. *2,* Nris 6 and 7, p. 81 and 97, 1900.)

Zur Physik des Vulkanismus. (Geol. Fören. Förh. *22,* 26, 1901.)

Über die Wärmeabsorption durch Kohlensäure. (Öfversigt 1901, No. 1, p. 25. Drudes Ann. *4,* 689, 1901.)

Zur Kosmogonie. (Archives Néerlandaises. Ser. II, Tom. 6, p. 862, 1901.)

Lehrbuch der kosmischen Physik. (Hirzel, Leipzig 1903, 2 volumes. Russian translation, »Fisica Njeba», A. R. Orbinsky, 1905.)

On the physical nature of the solar corona. (Lick Observatory Bulletin, *58,* 188, 1904.)

On the electric charge of the Sun. (Terr. magnetism, *10,* 1905. Proc. Roy. Soc. *73,* 496, 1904. Electrical Congress, St. Louis 1904, *1,* 274.)

The relation of meteorology to other sciences. (Congress of arts and sciences. St. Louis, 1904, *4,* 733.)

Om solens korona. (Nordisk Tidskrift, 1905, 1.)

Lifvets utbredning genom världsrymden. (Nordisk Tidskrift, 1905, 189.)

Die vermutliche Ursache der Klimaschwankungen. (Medd. *1,* No. 2, 1906.)

Die Nordlichter in Island und Grönland. (Medd. *1,* No. 6, 1906.)

Världarnas utveckling. (H. Geber, Stockholm, 1906; 6th edition 1909. 7th revised ed. 1917. 8th revised ed. 1924 and partly posthumous 1929, ed. Knut Lundmark. German edition: Werden der Welten, Akad. Verlagsges. Leipzig 1908, and 1913. English edition: Worlds in the making, Harper and Brothers, London 1908. Finnish edition, Otava 1907. Italian and Russian editions 1909. French edition: L'évolution des mondes, Paris, Béranger, 1909.)

De kosmogoniska ideernas utveckling. (Ord och Bild, 1907, 65.)

Människan inför världsgåtan. (H. Geber, Stockholm, 1907. German edition: Vorstellungen vom Weltgebäude im Wandel der Zeiten, Akad. Verlagsges. Leipzig 1908. English edition: The life of the Universe, Harper and Brothers. London and New York 1909.)

Zur Frage nach der Unendlichkeit der Welt. (Arkiv för Matem., Astr. o. Fysik, *5,* No. 12, 1908.)

Emanuel Swedenborg as a cosmologist, in: Em. Swedenborg II, Cosmologica, p. 13.

Die Unendlichkeit der Welt. (Scientia, Riv. d. Scienzia. *5,* 1909.)

Die physikalischen Grundlagen der Kohlensäuretheorie der Klimaveränderungen. (Zentralbl. f. Mineralogie etc. 1909, 481.)

Nordlicht mit Gewitter. (Medd. *2,* No. 4.)

Der Planet Mars nach neueren Untersuchungen. (Deutsche Revue 1910.) (Swedish version: Nordisk Tidskrift, 1910, 81.)

Die Atmosphären der Planeten. (Ann. d. Naturphilosophie, *9,* 70.) (Swedish version: Nordisk Tidskrift 1910, 453.)

Den Halleyska kometen. (Nordisk Tidskrift 1910, 171.)

Über den Ursprung des Gestirnkultus. (Scientia, Riv. di Scienzia, *9,* 1911.)

Das Schicksal der Planeten. (Akad. Verlagsges. Leipzig 1911.)

Das Weltall. (Kröner, Leipzig 1911.)

Zur Physik der Salzlagerstätten. (Medd. *2,* No. 20, 1912.)

Die Verteilung der Himmelskörper. (Medd. *2,* No. 21, 1912.)

Über die physikalischen Bedingungen bei den Salzablagerungen zur Zeit ihrer Bildung und Entwicklung. (Kali, *6,* 361.)

Zur Physik der Salzlagerstätten. (Die Umschau, *16,* 777, 1912.)

Das Milchstrassensystem. (Nord und Süd, *36,* 180, 1912.)

Vintergatan. (Nordisk Tidskrift, 311, 1912.)

Die Milchstrasse. (Prometheus, *24,* 32 and 52, 1912.)

Ueber den Ursprung des Gestirnkultus. (Das monistische Jahrhundert, 1912, p. 41 and 89, München.)

Die physikalisch-chemischen Bedingungen bei der Bildung der Salzlagerstätten und ihre Anwendung auf geologische Probleme. (Geologische Rundschau, *3,* 139, 1912.) (With R. Lachmann.)

Der gegenwärtige Stand der Mondforschung. (Neue wissenschaftliche Rundschau, 85, 1913.)

Quelques remarques sur l'énergie du soleil et des astres. (Journ. de Chimie Physique, *14,* 341, 1916.)

Stjärnornas öden. (H. Geber, Stockholm 1915.)

Klimatiska ändringar. (Forhandlinger ved 16. skand. naturforskermöte i Kristiania 1916, p. 28, 1917.)

Nyare undersökningar af nebulosor. (Vetenskapen och lifvet 1917, p. 98, 236, 342.)

Nyare undersökningar om norrsken. (Vetenskapen och livet, *4.* No. 16.)

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Part IV. The Arthropoda: Crustacea and Chelicerata

NUTRITIONAL IDIOSYNCRASIES OF *ARTEMIA* AND *TIGRIOPUS* IN MONOXENIC CULTURE*

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Introduction

While the nutrition of insects is a well-developed subject, we know little about the nutritional requirements of Crustacea (Beerstecher, 1952). Most of the nutritional work has been done with bacterized cultures and on the few species that lend themselves to laboratory conditions, such as *Daphnia*, *Moina*, and *Artemia*, or on such ecologically important species as *Calanus*.

The ecologist is interested in defining the role of algae, bacteria, and detritus in zooplankton nutrition; the ecological implications of the trophic relations of the crustacean zooplankton are discussed by Edmondson (1957) in a brilliant review. Although bacterized cultures are extremely useful for such types of research as life cycles and genetic and population studies, knowledge of the nutritional requirements must rest ultimately on axenic cultures. The availability of many species of fresh-water and marine algae in bacterium-free culture permits the monoxenic cultivation of Crustacea, thus determining whether the algae can be the sole source of food and which of them are utilized. Gibor (1956) and we have shown that some algae can be the primary source of food, and we confirm previous observations, from studies made with bacterized cultures, that different Crustacea prefer or need different food organisms. Often closely related species may constitute either good or bad food. In order to find whether this depends on a nutritional inadequacy it is necessary to grow the Crustacea on nonliving food and then identify their nutritional requirements in chemically known media. This knowledge may clarify the puzzling food specificity of Crustacea.

This paper deals with the preliminary phase of such a study—the monoxenic culturing of *Tigriopus* (FIGURE 1) and *Artemia*, the latter selected because of its resistance to many environmental factors. We are now trying to culture *Artemia* on nonliving food. The present artificial media allow development to the full-grown IV metanauplii, but not yet to adults.

Techniques

Bacterium-free cultures. Culturing techniques vary depending on whether the organism to be cultured has a relatively impervious stage, as in the heavily keratinized eggs of Crustacea living in waters that dry up periodically.

For the resistant eggs of *Artemia*, we use Gibor's technique with slight

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modifications. A few hundred eggs are put at the bottom of a sterile screw-cap tube (20 × 125 mm.) filled almost to the top with sterile sea water. The tube is closed, shaken vigorously to break up the clumps of eggs, and then left upright. The lighter eggs are decanted and eliminated by 2 or 3 flotations; the tube is then filled with Merthiolate solution (1:1000 in H_2O) to which is added a 10 per cent solution of Aerosol OT (0.2 ml./100 ml.) to improve wetting. The Merthiolate is changed 3 times in the 10-min. period of disinfection, and the tube is continuously shaken. The disinfectant is then decanted and the eggs washed by filling the tubes 3 times with sterile sea water. The sea water is decanted almost completely and the egg slurry transferred with a pipette to several tubes of medium STP (a sea water medium enriched with trypticase, yeast extract, and sugar; see composition below) and allowed to hatch. Hatching and sterility testing are, therefore, simultaneous. The metanauplii are transferred by Pasteur pipette to tubes with food organisms. The failures are caused chiefly by the presence of cracked, dead eggs that cannot be disinfected in the short time tolerated by the fertile ones, even with the addition of wetting agents. Hence, the dead eggs must be eliminated; since they are lighter, this can be done either by centrifugation or by flotation in sea water or in a denser solution (5 to 10 per cent NaCl).

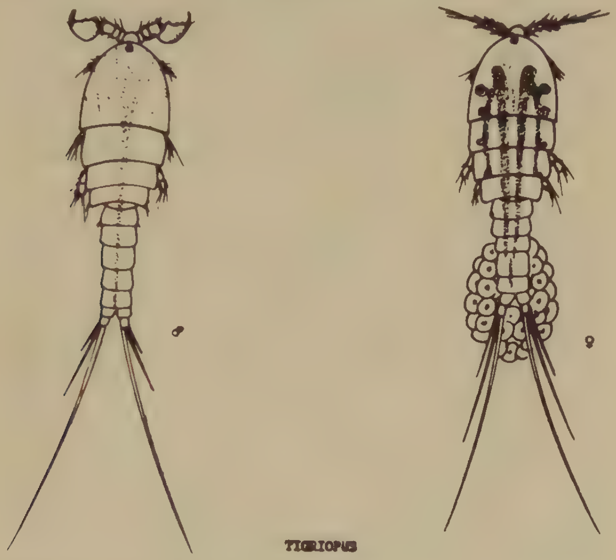

FIGURE 1. *Tigriopus:* male (left) and female carrying egg sac.

Crustacea lacking resistant stages, such as the *Cladocera*, the group most studied, can be made bacterium-free by washing larvae or adults. Fifteen serial washings in sterile media resulted in 80 to 90 per cent bacterium-free *Moina macrocopa* (Stuart, Tallman, and Cooper, 1931; Stuart, McPherson, and Cooper, 1931). Similar procedures work for other *Cladocera* (Gellis and Clarke, 1935), and were used to obtain bacteria-free *Tigriopus*. To eliminate difficulties deriving from bacterial infection of the gut at the onset, one may select for washing either newborn nauplii or young larval forms that still depend on the yolk for growth; that is, before they have started feeding. The egg sacs of *Tigriopus* are green when immature and red when containing embryos ready to hatch (FIGURE 2*a*). We found that the nauplii (FIGURE 2*b*) of *Tigriopus* hatch in about 1 hour if the red egg sac is put near an incandescent lamp.

The following technique was developed. Two to three females carrying red egg sacs are allowed to swim actively for 10 min. in each of 3 successive baths of 40 ml. of sterile sea water. The females are then transferred to a dry depression slide, superfluous water is eliminated to prevent active swimming, and the egg sac is removed with a sterile needle (FIGURE 2c). The egg sacs are washed 3 times in 20 ml. of sterile sea water by drawing them repeatedly in and out of a sterile pipette. Each egg sac is then transferred to a depression slide containing 1 ml. of liquid. We employ thick Pyrex slides (with 3 depressions—each depression is of 1-ml. capacity), which are sterilized in a deep Petri dish. The Petri dishes are placed near an incandescent lamp until the nauplii are hatched (about 1 hour). The nauplii are then transferred through 9 sterile baths of 1 ml. each, and inoculated singly in media with aseptic food organisms. The nauplii are phototactic and congregate at the surface of the liquid, rendering it easy to fish them out by capillarity with a Pasteur pipette drawn to a capillary large enough to allow passage of a single nauplius. Thus a minimum of water is drawn in with the nauplii. In preliminary tests 9 washes or more resulted in aseptic nauplii; however, when we have employed this technique regularly, washing more than 100 per day, only 50 per cent of the nauplii were aseptic.

Tigriopus can withstand antibiotic mixtures for about 1 day; longer periods in antibiotics cause increasing mortality. Apparently *Daphnia*, also, is not particularly resistant to penicillin and streptomycin when these compounds are employed in the media to decrease bacterial growth (Beerstecher and Harper, 1951). The antibiotic treatment alone, even when carried on for the longest safe time, did not result in bacterium-free cultures. By combining the two techniques we obtained 100 per cent aseptic nauplii.

In the technique followed with *Tigriopus*, 10 females with red egg sacs are washed in 3 baths (30 min. immersion in each bath) of 20 ml. of sterile sea water containing an antibiotic mixture. The removed egg sacs are washed 3 times in the sea water–antibiotic mixture, and then each is placed in a separate depression and hatched near a lamp. The nauplii are washed in 6 successive baths composed of 1 ml. of sea water and 0.2 ml. of antibiotics. We add to every 10 ml. of sterile sea water 2 ml. of the antibiotic mixture AM 9, 1 ml. of which contains: dihydrostreptomycin, 5000 μg.; potassium penicillin G, 5000 u.; polymyxin B sulfate, 150 u.; tetracycline, 250 μg.; chloramphenicol, 50 μg.; and neomycin, 250 μg., the whole sterilized by glass filtration. One milliliter of another useful mixture (AM 4) contains: potassium penicillin G, 12,000 u.; chloramphenicol, 60 μg.; polymyxin B sulfate, 60 u.; neomycin, 60 μg. This more dilute antibiotic solution has

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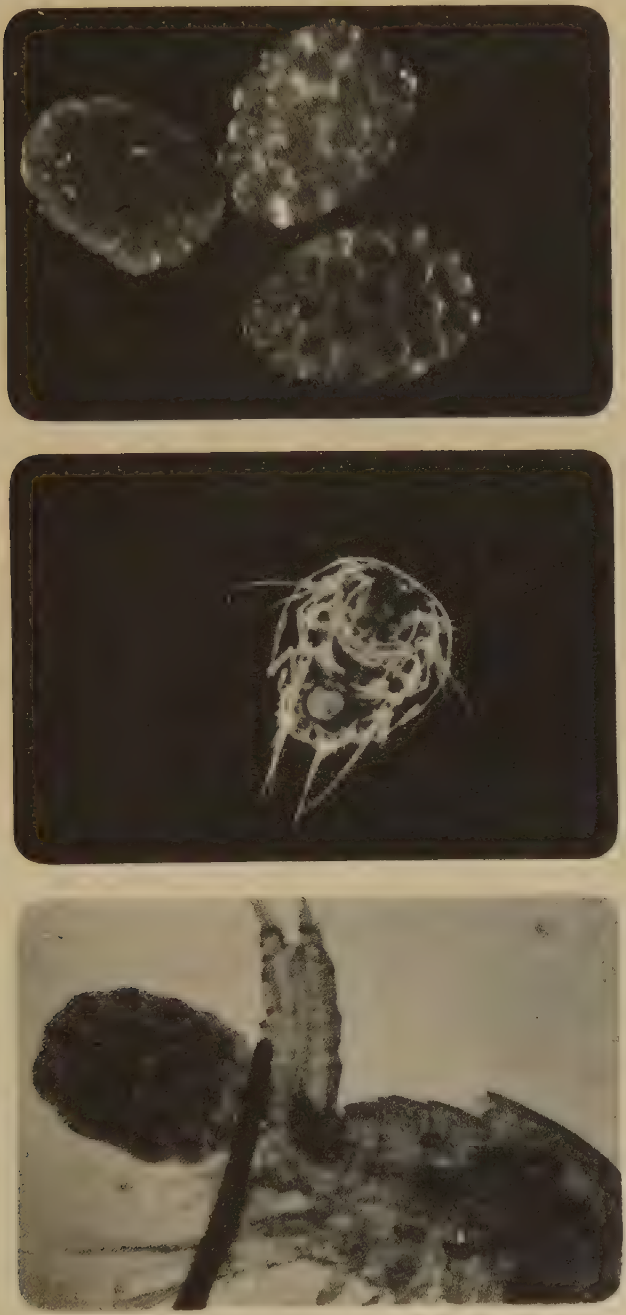

FIGURE 2. Top: immature (green) egg sacs of *Tigriopus*, and a red egg sac with embryos ready to hatch. Center: late nauplius stage. Bottom: red egg sac being removed with needle. Color transparencies by James R. Lance, subsidized by the Kaiser Foundation Research Institute, Laboratory of Comparative Biology, and by the Scripps Institution of Oceanography, Marine Life Research Program, La Jolla, Calif.

been employed to sterilize a mixture of nauplii and copepodites. The larvae were washed 6 times in 1 ml. of sterile sea water plus 0.2 ml. of antibiotic mixture and a suspension of living bacterium-free *Platymonas*, then left for 48 hours or overnight in the last bath. During this period the larvae molted and were washed another 6 times in antibiotics before being inoculated in test tubes containing living food. Although in most cases bacterium-free *Tigriopus* were obtained, the washing of advanced larval stages is less dependable, and it is advisable only if it is impossible to work with newborn nauplii. The success of the washing is enhanced by employing the antibiotic mixtures at the highest nontoxic concentration (letting them act as long as possible), by selecting organisms that have just molted (to avoid excessive bacterial inquinations deriving from the exoskeleton), and by adding bacterium-free living algal food so that a rapid discharge of feces is obtained during the washing procedure. We believe that these procedures are widely applicable to other marine Crustacea.

Culturing techniques. The medium employed for growing the food organisms and for the feeding experiments is sea water enriched with: Miquel solution A, 1 ml.; Miquel solution B, 0.5 ml.; soil extract, 20 ml.; STP medium, 50 ml.; sea water to 1 l., the whole with a pH of 7.7.

Miquel solution A is made of 22.2 gm. KNO_3 per 100 ml. H_2O. Composition of Miquel solution B is as follows: $Na_2HPO_4 \cdot 12H_2O$, 4 gm.; Ca (as chloride), 0.73 gm.; Fe (as chloride), 16 mg.; HCl (conc.), 2 ml.; and H_2O, 80 ml.

STP medium is composed of: sea water, 80 ml.; H_2O, 15 ml.; soil extract, 5 ml.; KNO_3, 20 mg.; K_2HPO_4, 1 mg.; Na-H-glutamate, 50 mg.; glycine, 10 mg.; DL-alanine, 10 mg.; trypticase (BBL), 20 mg.; yeast autolysate (Difco), 20 mg.; sucrose, 0.1 gm.; vitamin solution No. 8,* 0.1 ml.

While this medium is not optimal for each of the food organisms, it allows good growth, in 15 to 20 days, of nearly all the photosynthetic species; it is a poor medium for *Stichococcus*, *Peridinium*, *Gyrodinium*, and *Eutreptia*. All the experiments were done in 20- × 125-mm. screw-cap tubes containing 5 ml. of medium.

Algal stock cultures are transferred once a month; cultures to be used as food are inoculated with 0.5 to 1 ml. of a full-grown culture 3 to 10 days before introducing *Tigriopus* or *Artemia*.

The *Tigriopus* cultures are started by inoculating 2 to 4 newborn nauplii in each tube. For each food organism we inoculate 4 tubes; 2 of them with nauplii from one egg sac, 2 from another. This is to avoid the possibility of obtaining all males or females, as happened in preliminary experiments with *T. californicus*. In this species the deviation in sex ratio can be quite conspicuous, and often the brood of one egg sac is composed of 75 to 100 per cent males. Ar-rushdi (personal communication), after a detailed study, assumes that sex determination in *Tigriopus* is polygenic.

On reaching maturity, a male and a female derived from different egg sacs are transferred to a separate test tube and allowed to copulate. Each red egg sac–carrying female is then transferred to a new culture of food organisms. The isolation of egg-carrying females is necessary because the newborn nauplii are often devoured by the adults—especially by the males. For this reason, when the nauplii hatch, the female is removed aseptically, and the nauplii of the next generation are allowed to reach maturity undisturbed. From the F_1 on, we do not cross two different strains, but allow the adults derived from one egg sac to inbreed. Two females carrying red egg sacs are isolated every generation, and their progeny are allowed, likewise, to grow to maturity and copulate. We did not observe drastic changes of sex ratio in *T. japonicus.* The reason for adding STP (5 ml./100 ml.) to the Miquel-sea water medium was to enrich the sea water with organic nutrients that would favor the growth of contaminants. Gross infections are detected soon in the bimembered cultures because, after each transfer, the food organisms are not abundant, and opalescence of the medium is easily detected. Toward the end of each generation, however, it is impossible to detect infections visually, owing to the abundant growth of algae; besides, the medium often becomes opalescent as a result of the growth of both the crustaceans and the algae. Therefore, when the females bearing red egg sacs are removed from the old culture tube to carry on the next generation, the medium is tested for purity by inoculating 0.5 ml. in a tube containing STP medium agarized to a semisolid consistency (0.3 per cent agar).

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* See page 408 in Provasoli *et al.* (1957). This mixture can be replaced with: vitamin B_{12}, 0.02 μg. per cent; biotin, 0.1 μg. per cent; thiamine, 10 μg. per cent.

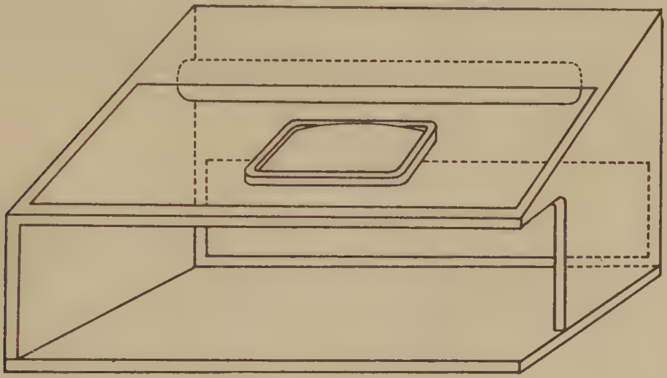

FIGURE 3. Transfer hood.

Fishing fertile females from a culture is not easy. One uses a Pasteur pipette connected to a rubber mouthpiece and, since the test tubes remain open for a long time during the fishing process, many infections result at first. We decided to employ a modified transfer hood (FIGURE 3). The box is open laterally and in front to facilitate manipulations; sterility is maintained by a Letheray germicidal ultraviolet lamp. Part of the top and back of the box is glass; outside, close to the rear glass panel, a strong light source is placed and adjusted to illuminate the test tubes that are held almost horizontally during transfers. A 2- × 4-in. Bausch and Lomb reading glass, placed on the inclined glass panel, gives magnification sufficient to distinguish males from females bearing egg sacs.

Results with Tigriopus californicus

The first experiments on *Tigriopus* were carried out with this species, and with *Platymonas* No. 5 as the food organism. In the initial successful bacterium-free culture all the nauplii became males, which prompted an analysis by Ar-rushdi of the factors determining sex ratio. *T. californicus* was purified by washing a total of 340 nauplii; no antibiotics were employed. In one experiment, 30 per cent of the nauplii were aseptic and, in another, 50 per cent; the sex ratio was 2 males to 1 female. All the bacterium-free females were mated, making, in all, 44 aseptic crossings.

Although copulation and development of egg sacs seemed normal, there was high mortality among the F_1 larvae. Few larvae became adults, and those that did were only half the normal size. The F_1 adults copulated occasionally, and only one female produced an egg sac, which was small and contained eggs that showed no embryonic development.

The same *Platymonas* in bacterized cultures has allowed continuous culturing of *T. californicus* for the past 3 years.

Results with Tigriopus japonicus

After failure to obtain permanent bacterium-free cultures of *T. californicus*, we tried *T. japonicus*, which seemed more vigorous in bacterized cultures. The nauplii were purified by washings in antibiotic mixtures. Various algae were tried in the hope of finding food organisms more suitable than *Platymonas*. All the algae selected are of a size acceptable to the nauplii (6 to 15 μ). Only a few of the 20 organisms tested carried *Tigriopus* through several generations: *Platymonas*, *Isochrysis*, *Monochrysis*, *Chroomonas*, and

TABLE 1
DAYS REQUIRED BY NAUPLII OF *Tigriopus japonicus* TO REACH ADULTHOOD

Food Organism	Generation										
	P	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{11}
Chlorophyceae											
Platymonas sp. (La Jolla)	11	12	16–21*								
Platymonas sp. (No. 5)	11	11	9	9	11	15	18	14–17*→†			
Chrysophyceae											
Stichochrysis immobilis	13	12*									
Isochrysis galbana	11	10	10	11	13	14	14	12–20	15–19*		
Monochrysis lutherii	11	10	13	14	19	17	19	20→			
Cryptophyceae											
Rhodomonas lens	11	10	12	14	13	18*					
Chroomonas sp.	11	9	11	10	12*						
Mixed food											
Platymonas sp. (L.J.) + *Isochrysis*	11	11	10	10	11	14	19*				
Platymonas sp. (L.J.) + *Rhodomonas*	11	9	10	13	14	16	19*				
Rhodomonas + *Isochrysis*	11	11	11	10	10	10	13	10	9	9	10→

* High mortality at nauplius or copepodite stage; lack of copulation or egg fertility.

† Arrow represents continuing culture. Since the preparation of this article (April 1958), additional information has become available. Results (January 1959) are as follows: *Platymonas* sp. (No. 5) ceased to support growth of *Tigriopus* at the F_8. The culture fed on *Monochrysis lutherii* is now at the F_{18}, and the culture fed on *Rhodomonas* plus *Isochrysis* is at the F_{26}.

Rhodomonas. Two generations were obtained with *Eutreptia* and *Stichochrysis*, and only one, the parental, with *Hemiselmis*, *Syracosphaera*, and *Nannochloris*. Nauplii reared with *Dunaliella*, *Stephanoptera*, *Stichococcus*, *Brachiomonas*, and *Pyramimonas* reached, at best, the copepodite stage.

Although in lesser degree than for *T. californicus*, prolonged culturing on one food organism causes gradual lengthening of the time required by the nauplii of *T. japonicus* to become adult (TABLE 1). Copulation and production of egg sacs are also gradually delayed. Later, the mortality of the larval stages increases drastically, and only four to five of the twenty to thirty larvae hatched from a normal egg sac become adults; these adults do not copulate, but some infertile eggs may be produced. This deterioration occurs sooner or later, depending on the food organism. It is probable that all the monoxenic cultures will die soon, because all now show to some degree the aforementioned signs. We hope, however, that the cultures fed on the combination *Rhodomonas-Isochrysis* will persist indefinitely.*

Results with Artemia salina

The eggs were disinfected with Merthiolate and inoculated directly in STP, which serves as a hatching and sterility test medium. The yolk permits development up to the second metanauplius; this stage is reached four to five days after inoculation of the eggs. The second metanauplii are then inoculated into tubes containing the different food organisms. The results given are based on one generation, as are those of Gibor, and are, therefore, comparable to the results with the parental generation of *Tigriopus.* Further deficiencies in fertility or growth may appear in later generations. We have not grown *Artemia* for successive generations; this can be done by drying the durable eggs aseptically for one month before they are hatched.

Dunaliella sp. (marine), *Platymonas* No. 5, *Stephanoptera*, *Brachiomonas*, *Stichochrysis*, *Isochrysis*, *Syracosphaera*, *Rhodomonas*, *Hemiselmis*, and *Chroomonas* are all favorable food; however, adulthood is reached most rapidly (in sixteen days) when *Artemia* is fed on *Stephanoptera*, *Rhodomonas*, or *Brachiomonas* (TABLE 2). Other organisms such as *Stichococcus* and *Gyrodinium* are either poisonous or nutritionally inadequate, because the larvae do not even molt to the third metanauplius. *Platymonas* (L.J.), *Nannochloris*, and *Peridinium* permit molting to the third metanauplius, and *Dunaliella* (brine), *Pyramimonas*, *Monochrysis*, and *Eutreptia* allow molting to the fourth metanauplius. Our results are in accord with those of Gibor, who found that *Dunaliella viridis* and *Stephanoptera gracilis* or *D. salina* and *Platymonas* sp. permit development to adults (growth with the latter two is slower), and that *Stichococcus* is an inadequate food organism.

Discussion and Conclusions

Tigriopus and *Artemia* display a diverse ability to utilize different species of algae as food. This selectivity does not depend on the size of the food organism, which varies between 6 and 15 μ, a size acceptable to the larval forms of both species. Similar results were obtained by Lefèvre (1942) with

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* See footnote (†), TABLE 1, for more recent data.

TABLE 2
UTILIZATION OF FOOD ORGANISMS BY *Artemia* AND *Tigriopus*

Food Organisms	*Artemia salina*		*Tigriopus japonicus*		*Art.*	*Tigr.*
	Stage reached	Days to adult stage	Stage reached (1st generation)	No. generations obtained		
Chlorophyceae						
Dunaliella sp. (brine)	L*		L		○	○ ‡
Dunaliella sp. (marine)	A	18	L		●	○
Platymonas sp. (La Jolla)	L		A	3	○	●
Platymonas sp. (No. 5)	A	28	A	8→ †	●	●
Nannochloris oculata	L		A	1	○	○
Stephanoptera sp.	A	16	L		●	○
Stichococcus fragilis	L		L		○	○
Brachiomonas pulsifera	A	16	L		●	○
Pyramimonas inconstans	L		L		○	○
Chrysophyceae						
Isochrysis galbana	A	18	A	9	●	●
Monochrysis lutherii	L		A	8→	○	●
Stichochrysis immobilis	A	18	A	2	●	○
Syracosphaera elongata	A	18	A	1	●	○
Cryptophyceae						
Chroomonas sp.	A	18	A	5	●	●
Hemiselmis virescens	A	18	A	1	●	○
Rhodomonas lens	A	16	A	6	●	●
Eugleninae						
Eutreptia sp.	L		A	2	○	○
Dinophyceae						
Gyrodinium cohnii	L		L		○	○
Peridinium sp.	L		L		○	○

* Key: L, larval stages; A, adult.

† Arrow represents continuing culture. See footnote (†), TABLE 1.

‡ A closed half-circle indicates a food organism that supports growth to adulthood of *Artemia* (*Art.*), or more than two generations of *Tigriopus* (*Tigr.*); a closed circle, one that supports growth of both organisms; and an open circle, growth of neither organism.

Daphnia and by Gibor (1956) with *Artemia*. Even in closely related species of algae, one organism may be nutritionally suitable, the other unsuitable. Thus for *Daphnia*, *Scenedesmus spinosus* is an excellent food, but *S. oahuensis* and *S. quadricauda* are mediocre or poor; *Cosmarium impressulum* is good, while *C. tetraophthalmum* allows no growth (Lefèvre, 1942). Gibor found that *Dunaliella viridis* is better than *D. salina* for *Artemia*. Similarly, we find that *Artemia* reaches adulthood if fed on one strain of *Dunaliella*, but that another strain allows growth only to the IV metanauplius. The same difference was found between strains of *Platymonas*. Although we tried only twenty species, and although any conclusion has a limited value, *Artemia* differs from *Tigriopus* in its ability to utilize more species of Chlorophyta as food.

What determines the suitability of an alga as food? Naumann has shown that some algae remain alive after passing through the digestive system of an invertebrate; this is confirmed by Gibor for *Stichococcus* and *Artemia*. Apparently one of the factors affecting utilization of the algae is the thickness of the cell wall; von Dehn (1930) found that *Daphnia magna* cannot digest the cellulose wall of *Chlorella vulgaris* or of *Stichococcus bacillaris*, although it can digest and absorb the contents of these cells. It is doubtful, however, that this is responsible for the different nutritional values of two species belonging to the same genus (note examples given above).

It is more likely that the suitability of an organism as food depends on its chemical composition; the following circumstantial evidence seems to support this hypothesis.

(1) *Tigriopus californicus* can reproduce for only 2 generations when *Platymonas* No. 5 is the only food, but has been cultured 3 years on the same *Platymonas* in the presence of an unidentified bacterial flora. Similarly, different food organisms support varying numbers of generations of *T. japonicus* before larval mortality and adult infertility intervene.

(2) While the cultures of *T. japonicus* on *Rhodomonas* died at the sixth generation and the culture on *Isochrysis* has been declining since the eighth, cultures fed on the mixture *Rhodomonas-Isochrysis* are now in the eleventh generation with no evidence of degeneration or lengthening of generation time (footnote (†), TABLE 1).

(3) *Isochrysis* and *Rhodomonas*, which are among the best food organisms for *Tigriopus* and are good for *Artemia*, are also good food organisms for oyster larvae (Bruce *et al.*, 1940; Davis and Guillard, 1958) and for adult oysters (Dean, 1957).

It is evident that algae, like *Isochrysis* and *Rhodomonas*, which permit several monoxenic generations of *Tigriopus* and serve also as food for *Artemia*, most nearly supply all the necessary nutrients and may, therefore, be a good food for other, unrelated invertebrates if their size permits ingestion. However, their failure to support an indefinite number of generations of the predator indicates that their production of a necessary nutrient is at a suboptimal level. This factor is quite probably a micronutrient (perhaps a growth factor), since many generations are required before its lack causes mortality of larvae and infertility of adults. Indeed, the lack of some vitamins induces the same effects in insects. Fritsch (1953) found that the addition of 200 mg./l. of pantothenic acid to cultures of *Daphnia* fed on *Chlamydomonas* tripled the life span and increased egg production tenfold.

Platymonas No. 5 supports only 2 generations of *T. californicus* and 8 of *T. japonicus*. This may indicate that the two *Tigriopus* species either have different nutritional requirements, or that *T. californicus* needs higher levels of a necessary nutrilite that is sparingly produced by *Platymonas*.

These partial deficiencies can be overcome by adding other food organisms: bacteria or other algae. Greater deficiencies in nutrients, imbalances, production of toxic metabolites, or overproduction of a needed metabolite may all account for the failure of an alga to support even one generation of the predator.

The deficiency hypothesis, while not accounting entirely for the differential utilization of algae as food, offers a means of attacking the problem experimentally. In fact, by utilizing algae that are poor food organisms, it might be possible to identify (as for *D. magna*) some of the nutritional requirements of Crustacea and, by inference, to provide a biological analysis of constituents of the algae.

Although useful, monoxenic cultures are only a first step toward the necessary goal of growing the Crustacea in chemically defined media and of thus identifying their nutritional requirements. The intermediary step of growing Crustacea axenically has been already achieved by Treillard (1924), who succeeded in culturing *Daphnia* on red blood cells suspended in a mineral solution and glucose and on other complex sterile media. We have found it expedient to employ *Artemia* for similar attempts and, by using a comparably complex medium, we have obtained fully developed axenic IV metanauplii but, as yet, no adults.

Gibor (1956) and Edmondson (1957) emphasize the ecological importance of the nutritional specificity displayed by Crustacea which, as already noted, is confirmed and extended by our results. The composition in species of phytoplankton, therefore, becomes critical, and chlorophyll data as an index of the quantity of phytoplankton mean little if not complemented with taxonomic data. It may be comfortable to assume that in many food chain studies there is no obligation to identify the constituent species, but this assumption is unwarranted. Furthermore, a taxonomic list of all species involved is insufficient; we must know not only the algal species ingested and digested, but also their nutritional value for the herbivorous predators. Gibor's experiments make this point: *Artemia* in a mixed culture of *Stichococcus* and *Dunaliella viridis* ingests both algae, but digests completely only *Dunaliella*; many *Stichococcus* cells are recovered alive from the feces. The result is a flourishing growth of *Artemia* in an excellent culture of *Stichococcus* and a very poor culture of *Dunaliella*. This is exactly what is found in brine ponds inhabited by these three organisms. The differential removal of the two algae would have made very difficult the ecological analysis of this niche, to say the least, while laboratory experiments easily explain the field data.

Even when an apparent correlation is found between qualitative and quantitative measurements of the phytoplankton and zooplankton growth, it should still be determined whether zooplankton growth actually depends on the dominant phytoplankton species. Our experiments show that bacteria and other algae can supplement, and make nutritionally adequate, species of algae that, alone, cannot support the growth of the predator. It is most likely that this nutritional supplementation prevails in nature, and this is to be suspected when a predominant alga seems to be the important food of a marine herbivore in certain locales, but fails to be so in others: a hint that the accompanying bacterial and algal flora are important.

The experimental approach to marine ecology during recent years substantiates more and more the decisiveness of interrelationships between organisms in the water environment; these relationships can be direct, often nutritional (as that discussed here), or mediated by the "external metabolites" postulated by Lucas (1955). We can ignore these complexities at the price of a dim notion of reality, or we can delight in the systematic disclosure of ever vaster and subtler secrets.

References

Beerstecher, E. 1952. The nutrition of Crustacea. Vitamins and Hormones. **10**: 69.

Beerstecher, E. & R. M. Harper. 1951. Unpublished data. *In* Beerstecher. 1952. The nutrition of Crustacea. Vitamins and Hormones. **10**: 72.

Bruce, J. R., M. Knight & M. Parke. 1940. The rearing of oyster larvae on algal diet. J. Marine Biol. Assoc. United Kingdom. **24**: 337.

Davis, H. C. & R. R. Guillard. 1958. Relative value of ten genera of micro-organisms as food for oyster and clam larvae. Fishery Bull. 136. U.S. Fish & Wildlife Service. **58**.

Dean, D. 1957. The experimental feeding of oysters. Ph.D. Thesis. Rutgers University. New Brunswick, N. J.

Edmondson, W. T. 1957. Trophic relations of the zooplankton. Trans. Am. Microscop. Soc. **76**: 225.

Fritsch, R. H. 1953. Die Lebensdauer von *Daphnia* spec. bei verschiedener Ernährung, besonders bei Zugabe von Pantothensäure. Z. wiss. Zool. **157**: 35.

Gellis, S. S. & G. L. Clarke. 1935. Organic matter in dissolved and colloidal form as food for *Daphnia magna*. Physiol. Zool. **8**: 127.

Gibor, A. 1956. Some ecological relationships between phyto- and zooplankton. Biol. Bull. **111**: 230.

Lefèvre, M. 1942. L'utilization des algues d'eau douce par les Cladocères. Bull. biol. France et Belg. **76**: 250.

Lucas, C. E. 1955. External metabolites in the sea. *In* Papers in Marine Biology and Oceanography. Deep-Sea Research. Suppl. **3**. Pergamon Press. London, England.

Provasoli, L., J. J. A. McLaughlin & M. R. Droop. 1957. The development of artificial media for marine algae. Arch. Mikrobiol. **25**: 392.

Stuart, C. A., M. McPherson & H. J. Cooper. 1931. Studies on bacteriologically sterile *Moina macrocopa* and their food requirements. Physiol. Zool. **4**: 87.

Stuart, C. A., J. Tallman & H. J. Cooper. 1931. Available food and crowding as factors influencing sex in *Moina macrocopa*. Physiol. Zool. **4**: 581.

Treillard, M. 1924. Sur l'élévage en culture pure d'un Crustacé cladocère: *Daphnia magna*. Compt. rend. **169**: 1090.

von Dehn, M. 1930. Untersuchungen über die Verdauung bei Daphnien. Z. vergleich. Physiol. **13**: 334.

(213)

Lower Eocene Phosphatized *Globigerina* Ooze from Sylvania Guyot

By EDWIN L. HAMILTON *and* ROBERT W. REX

BIKINI AND NEARBY ATOLLS, MARSHALL ISLANDS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-W

A study of the mode of occurrence,
mineralogy, and paleontology of
fossil Globigerina *oozes from*
Sylvania Guyot

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BIKINI AND NEARBY ATOLLS, MARSHALL ISLANDS

LOWER EOCENE PHOSPHATIZED GLOBIGERINA OOZE FROM SYLVANIA GUYOT[1, 2]

By Edwin L. Hamilton[3] and Robert W. Rex[4]

ABSTRACT

Dredge hauls on the top of Sylvania Guyot, the seamount adjacent to Bikini Atoll, Marshall Islands, were made by 1950 Mid-Pacific Expedition of the Scripps Institution of Oceanography and the U. S. Navy Electronics Laboratory. Sylvania has a very flat top at about 705 fathoms and is connected to Bikini Atoll by a saddle at a depth of 790 fathoms; the adjacent sea floor is deeper than 2,500 fathoms.

The dredge haul from Mid-Pacific station 43 A included tuff-breccia with cracks filled with a phosphatized fauna of earliest Eocene age dominated by *Globorotalia velascoensis* and *G. aragonensis;* the nearest faunal affinity of this assemblage, the oldest in the northern Marshall Islands, is with similarly occurring faunas from the Mid-Pacific Mountains about 1,000 miles to the east and with faunas from the Paleocene and Eocene deposits of the Tampico Embayment region of Mexico.

In the dredge hauls from Mid-Pacific stations 43 D and 43 DD, the fossil planktonic fauna was from the Miocene. The material from 43 D is correlated with the *Globigerinatella insueta* zone of the Caribbean; the material is about the same age as that found on Saipan.

The new evidence from Sylvania Guyot fits well into that previously determined and indicates the probability that in Late Cretaceous or earliest Tertiary time Sylvania was eroded to a flat bank; Bikini Atoll at this time was probably a younger and higher feature which had been little eroded. Fast subsidence in the Late Cretaceous or early Tertiary left Sylvania Guyot as a relatively deeply submerged flat bank while Bikini Atoll was at, or above, the surface. Subsequent submergence was relatively slow, so that a great reef grew on Bikini Atoll while planktonic Foraminifera were being deposited on the top of Sylvania Guyot.

INTRODUCTION

From 1946 to 1952 the most concentrated field study of coral atolls ever attempted took place in the northern Marshall Islands. Most of these studies are presented in other chapters of Professional Paper 260. As part of this effort the personnel of the 1950 Mid-Pacific Expedition sponsored by the U. S. Navy Electronics Laboratory and Scripps Institution of Oceanography made dredge hauls on Sylvania Guyot, the flat-topped seamount which lies northwest of Bikini Atoll. Sylvania Guyot and Bikini Atoll form a single twin-peaked massif which is connected by a saddle at a depth of 790 fathoms (fig. 255). Sylvania Guyot has a very flat top with depths of about 705 fathoms; it is about 14 by 30 miles across the top and is larger than Bikini Atoll. The geology of Bikini Atoll and Sylvania Guyot and details on the dredge hauls of this paper have been discussed by Emery, Tracey, and Ladd (1954) and will not be completely repeated here.

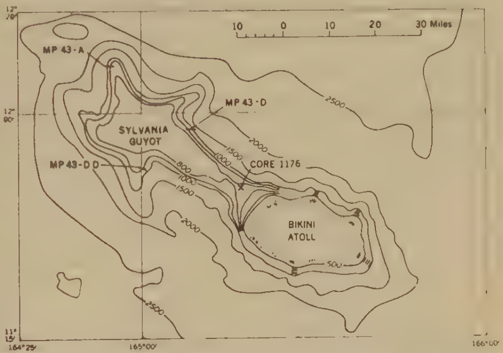

Figure 255.—Map of Bikini Atoll and Sylvania Guyot showing the locations at which dredge hauls were made.

One of the 1950 dredge hauls (MP 43 A) was made on a north spur of Sylvania Guyot at depths of from 1,030 to 810 fathoms, near the rounded edge of the flat top of the seamount (fig. 255). The dredged material consisted mostly of yellow and brown tuff-breccia covered by crusts of manganese oxide and containing irregular cracks filled with cemented Foraminifera (pl. 250); 1 rock was 24 inches long and weighed about 200 pounds and was covered by a $\frac{1}{16}$–$\frac{1}{4}$ inch crust of manganese oxide. Macdonald (Emery, Tracey, and Ladd, 1954, p. 120–121) identified this material as a friable tuff-breccia containing rock fragments in a fine matrix. Much of the tuff was altered to clay minerals. Macdonald believed this material was pyroclastic and was probably formed in waters much shallower than that from which the material was dredged. The fossil planktonic Foraminifera from the cracks and pockets of this tuff-breccia are from the earliest Eocene.

A second dredge haul (MP 43 D) was made on the southeast side of Sylvania Guyot, just below the break

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in slope, at depths between 1,150 and 820 fathoms (fig. 255). Part of this material was described by Macdonald as a much altered basaltic lava covered by a shell of manganese oxide.

In this latter material, uncemented Miocene *Globigerina* ooze was found in a small crack under the manganese.

A third dredge haul (MP 43 DD; fig. 255), made on a south spur of Sylvania at 880 fathoms, yielded a small "boulder" of partly indurated *Globigerina* ooze covered with a coat of manganese oxide. The planktonic Foraminifera of this indurated ooze are probably uppermost Miocene, but M. N. Bramlette (personal communication) thinks that the material may be Pliocene, on the basis of the coccoliths in the ooze.

This paper is concerned with the mode of occurrence, mineralogy, and paleontology of these fossil *Globigerina* oozes from the top of Sylvania Guyot and the significance of this material in the geologic history of the area. This material is important in the geologic history of the Pacific Basin because the early Eocene fauna is the oldest in the northern Marshall Islands area and is about the same age as the fossil Foraminifera on the submerged flat tops of the ancient islands of the Mid-Pacific Mountains to the east.

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The mineralogical study was by R. W. Rex and was supported by contract between the University of California, Scripps Institution of Oceanography, and the Office of Naval Research. The foraminiferal studies were by E. L. Hamilton.

OCCURRENCE OF FOSSILIFEROUS MATERIAL

MID-PACIFIC STATION 43 A

Vesicles and cracks in the palagonitized tuff from dredged material often contain buff Foraminifera embedded in a buff matrix. Detailed X-ray analysis and qualitative chemical tests of this buff material indicated that it is nearly pure apatite with only a small amount of calcium carbonate remaining. No chert crack fillings were noted (Macdonald *in* Emery, Tracey, and Ladd, 1954, p. 120). The process of phosphatization of the Foraminifera and other calcium carbonate particles is most complete for the matrix and least complete for foraminiferal tests and coccolith plates. Much of the phosphatized ooze has a dense buff crust, especially in areas where crusts of hydrogenous ferruginous manganese oxide have been deposited. The transition from apatite to crust of ferruginous manganese oxide is visually sharp; however, very small (1–30 microns) apatite particles form the principal nonferruginous manganese oxide part of this size range of the black crusts. The nonferruginous manganese part of the crust is 15 percent by weight of which 2 percent is apatite.

Detailed studies of the crystal structure, morphology, and surface area of the ferruginous manganese crust minerals have been made by Buser and Grütter (1956). The iron, according to these authors, is present as amorphous hydroxide and goethite, and the manganese, as delta-MnO_2 (Buser and Grütter, 1956, p. 51). The chemical composition of the ferruginous manganese crust from MP 43 A has been reported by Goldberg (1954, p. 252).

The paragenetic sequence which is suggested is as follows:

1. Deposition of Foraminifera and coccolith calcium carbonate remains in vesicles and cracks in the palagonitized tuff-breccia (pl. 250).

2a. Phosphatization of the calcium carbonate by orthophosphate ion substitution for carbonate in the solid calcium carbonate, probably according to the mechanism described by Clark and Turner (1955); this is essentially a replacement phenomenon.

2b. Dissolution of surface material in some cracks with reprecipitation of apatite to produce a dense crust over the loosely cemented ooze. This stage may have occurred before stage 2a, so that the solution and redeposition of calcium carbonate produced the hard crust. Evidence determining which step came first was not observed.

3. Sedimentation change from biogenous carbonate to hydrogenous ferruginous manganese crust containing a small quantity of 1- to 30-micron apatite particles. The X-ray powder diffraction pattern of these apatite particles is indistinguishable by spectrometer technique from the apatized Foraminifera. In addition, the presence of these apatite particles suggests that there are at least two mechanisms for production of apatite in equilibrium with sea water. Clark and Turner (1955, p. 665), in their discussion of the kinetically slow orthophosphate ion-solid calcium carbonate reaction, describe the first mechanism which is essentially a replacement of deposited calcium carbonate. If the foraminiferal form is preserved this mechanism is indicated. The second is a direct deposition of apatite particles from sea water. Because no calcium carbonate remains with the apatite of the ferruginous manganese crust and some does remain in the phosphatized ooze, it is concluded that calcium carbonate either was not deposited or was redissolved during deposition of the

ferruginous manganese crust. For this reason it seems improbable that the apatite in the ferruginous manganese crust could form after deposition from phosphatization of biogenous calcium carbonate. However, no evidence is available to indicate the precise mechanism of production of the apatite particles deposited directly from sea water. These particles do not show the small crystallite size characteristic of fishbone fragments or teeth. G. Arrhenius, M. N. Bramlette, and E. Picciotto (1957) have pointed out that the small apatite crystallites of fish debris which settle on ferruginous manganese crusts may dissolve and recrystallize as larger grains thereby decreasing their surface energy. The new apatite would then be in equilibrium with sea water, and the rare earths and thorium originally scavenged by the fish debris is sorbed on the ferruginous manganese phase.

The *d* spacings for the powder diffraction pattern of the apatized Foraminifera are given in the following table with corresponding values for apatized Foraminifera from Horizon Guyot and apatized biogenous calcium carbonate from Cape Johnson Guyot in the Mid-Pacific Mountains (for locations and geology see Hamilton, 1956). The powder-diffraction patterns from these seamounts are remarkably similar and differ only very slightly from a California continental-shelf phosphorite. The X-ray pattern corresponds to those of dehrnite and francolite (McConnell, 1938, p. 5), two different varieties of apatite. Further chemical studies would be necessary to ascertain which of these two varieties is the form present. Fluorapatite does not fit the marine apatite pattern as well as does francolite or dehrnite. Dietz, Emery, and Shepard (1942, p. 818) suggested that the California continental-shelf phosphorite be called francolite, basing their conclusion on the powder diffraction pattern and a fluorine content of about 3 percent. Dehrnite is a hydroxyapatite rich in sodium carbonate, and it may be that marine apatite precipitates as hydroxyapatite, the common aqueous precipitate (Clark, 1955, p. 1696), and then undergoes slow fluorine for hydroxyl substitution to gradually change to francolite.

X-ray diffraction analyses of apatite from seamounts and banks of the North Pacific compared with dehrnite, francolite, and fluor-apatite

All *d* values in Å. Measurements made with Norelco Diffractometer, CuKα, Ni filter, scanning ¼° 2θ per minute, 1° slits, 4 second time constant, and employing a rotating sample holder]

	Sylvania Guyot, MP-43A		Cape Johnson Guyot, MP-37C		Horizon Guyot, MP-25 F-2		Phosphorite, F. P. S. 183-5, Coronado Bank, San Diego, Calif.		Dehrnite (McConnell, 1938)[1]		Francolite (McConnell, 1938)[1]		Fluor-apatite (McConnell, 1938)[1]	
h, k, l	*d*	*I*	*d*	*I*	*d*	*I*	*d*	*I*	*d*	*I*	*d*	*I*	*d*	*I*
(002)	3.45	4	3.45	4	3.45	6	3.44	6	3.43	1	3.43	2	3.43	2
(102)	3.17	3	3.17	2	3.17	2	3.17	2	3.16	0.5	3.16	0.5		
(120, 210)	3.05	2	3.05	2	3.05	3	3.05	2	3.04	3	3.04	2	3.06	3
(300 β)	2.95	1			2.95	1			2.96	.5	2.96	.5	2.98	.5
(121, 211)	2.79	10	2.79	10	2.79	10	2.79	10	2.77	10	2.77	>10	2.80	>10
(112)	2.77	8	2.77	6	2.77	7	2.77	7					2.77	4
(300)	[illegible]	5	2.69	6	2.69	8	2.69	6	2.69	6	2.68	7	2.70	6
(202)	2.62	3	2.62	3	2.62	4	2.62	3	2.61	3	2.62	4	2.62	3
(301)	2.51	1	2.50	1	2.51	1			2.51	.5	2.51	.5	2.52	.5
(122, 212)	2.28	1			2.29	1	2.28	1	2.28	.5	2.28	1	2.29	.5
(130, 310)	2.24	2	2.24	3	2.24	3	2.24	3	2.23	4	2.24	3	2.25	2
(131, 311)	2.13	1	2.13	1	2.13	1	2.13	1	2.12	2	2.13	2	2.14	1
(113)	2.06	1	2.06	1	2.06	1	2.06	1	2.05	.5	2.06	1	2.06	1
(203)			2.00	1	2.00	1	1.99	1			2.00	1	2.00	.5
(222)	1.93	2	1.93	3	1.93	3	1.93	3	1.93	6	1.93	3	1.94	3
(132, 312)	1.88	1	1.88	2	1.88	2	1.88	2	1.88	2	1.88	1	1.88	1
(123, 213)	1.84	3	1.84	3	1.84	4	1.83	3	1.83	6	1.84	3	1.84	6
(231, 321)	1.79	1	1.79	2	1.79	2	1.79	1	1.79	2	1.79	2	1.80	3
(140, 410)	1.76	1	1.76	2	1.76	2	1.76	1	1.76	2	1.76	2	1.77	3
(402)	1.74	1	1.74	2	1.74	2	1.74	1	1.74	2	1.74	2	1.75	3
(004)	1.72	2	1.72	2	1.73	2	1.72	2	1.72	2	1.72	2	1.72	3
(232, 322)	1.63	1	1.63	1	1.63	1			1.63	1	1.63	.5	1.64	1

[1] McConnell's *d* spacings given here rounded off at second decimal place.

It should be noted that the paragenetic sequence and mineralogy of this material from Sylvania Guyot is identical with that for the phosphatized ooze from Horizon Guyot some 1,500 miles to the east. For the phosphatization of an expanse of ooze to take place, it is necessary that there be a cessation or marked diminution of the rate of accumulation; this is especially true if there has been a manganese crust deposited over the indurated material which is the case on Hess Guyot and Guyot 19171 in the Mid-Pacific Mountains.

MID-PACIFIC STATION 43 D

The *Globigerina* ooze in the cracks of the altered basalt of MP 43 D has been altered to phosphatic minerals in the same manner as the material from MP 43 A. This indicates that phosphatization was going on in the Miocene in the same manner as in the early Eocene.

MID-PACIFIC STATION 43 DD

This partly indurated, uppermost Miocene calcium carbonate ooze was in the form of a small boulder about

8 inches in diameter and was protected by a shell of manganese oxide about 6–10 millimeters thick. This material has not been phosphatized.

DESCRIPTION OF THE PLANKTONIC FORAMINIFERA

MID-PACIFIC STATION 43 A

The cracks and pockets inside the tuff-breccia from material dredged in haul MP 43 A contained the following fossil planktonic Foraminifera:

Globigerina apertura Cushman
  aff. *G. collactea* (Finlay)
  eocaena Gümbel
  mckannai White
  orbiformis Cole
  pseudobulloides Plummer
  rotundata d'Orbigny var. *jacksonensis* Bandy
  topilensis Cushman
  triloculinoides Plummer
Globorotalia aragonensis Nuttall
  centralis Cushman and Bermudez
  crassata (Cushman)
  crassata densa (Cushman)
  membranacea (Ehrenberg)
  velascoensis (Cushman)
  whitei Weiss
  wilcoxensis Cushman and Ponton

One crack contained an unusually well-preserved party phosphatized planktonic fauna. The crack was about half filled with the fossiliferous material. The top surface of the filling had an excellently preserved fauna which was lightly cemented together in the top part and was incorporated into the more indurated material on the bottom (pl. 251). The species of the material were easily identified. A distinctive feature of this fauna was that numerous specimens of *Globorotalia velascoensis* (Cushman) and *G. aragonensis* Nuttall appeared together, this allowed excellent age dating, as described below. The fauna of this and the other cracks was a *Globorotalia-Globigerina* planktonic fauna with very few benthonic species. The strongly keeled *Globorotalia* dominated the fauna.

The systematic descriptions of this, and the other fossil faunas will be found at the end of the paper together with plates which illustrate the main index species.

MID-PACIFIC STATION 43 D

The pocket, or crack, in the altered basalt and under the manganese crust, from material dredged in haul MP 43 D contained the following fossil planktonic Foraminifera:

Globigerina apertura Cushman
  bulloides d'Orbigny
  ciperoensis Bolli
  dissimilis Cushman and Bermudez
  ouchitaensis Howe and Wallace var. *senilis* Bandy
Globigerina rotundata d'Orbigny var. *jacksonensis* Bandy
  venezuelana Hedberg
Globigerinoides bispherica Todd
  rubra (d'Orbigny)
  sacculifera (Brady)
  subquadrata Bronniman
  triloba (Reuss)

As can be seen from the above list this was a *Globigerina-Globigerinoides* fauna; a distinctive feature is that no species of *Globorotalia* were identified, which is in sharp contrast with the fauna previously described from the Eocene. Stainforth (1949, p. 419) stated that the appearance of large-apertured species of *Globigerinoides* may be taken as evidence of postmiddle Oligocene; this mass aspect is certainly true of the Sylvania Guyot (MP 43 D) material.

MID-PACIFIC STATION 43 DD

The unindurated calcium carbonate ooze from dredge haul MP 43 DD contained the following fossil Foraminifera in addition to most of the planktonic species which occur in the Recent material from the area.

Globigerina altispira Cushman and Jarvis
Globorotalia menardii (d'Orbigny) var. *fijiensis* Cushman
  menardii (d'Orbigny) var. *multicamerata* Cushman and Jarvis
Sphaeroidinella multiloba LeRoy
  rutschi Cushman and Renz
  seminulina (Schwager)

With the exception of the above species, this fauna looks like the modern tropical planktonic fauna expectable in the area.

DISCUSSION AND CONCLUSIONS

AGE AND AFFINITIES OF THE FOSSIL FAUNAS

When the prolific, fossil, planktonic foraminiferal faunas of the Mid-Pacific Mountains were discovered, it was realized that these forms, so familiar in land deposits, were actually present all over the Pacific Basin and should be looked for and expected in ancient sea-floor deposits (Hamilton, 1953). The present study confirms this expectation and again presents the utility of the planktonic smaller Foraminifera in long-range time correlations.

MID-PACIFIC STATION 43 A

Studies of the mass aspects of fossil planktonic faunas by Henson (1938), Glaessner (1945), Tromp (1949), Reiss (1955), and others indicate that the *Globotruncana-Gümbelina* faunas of the Upper Cretaceous are replaced by the *Globigerina-Gümbelina* faunas of the Danian. In the Paleocene (Midway) and lower Eocene (Wilcox), the keeled Globorotalias are strongly represented, and the fauna is, in general, dominantly made up of *Globorotalia-Globigerina* species, which is the faunal type of the Sylvania samples from MP 43 A.

Several worldwide index species are represented in the MP 43 A fauna. The two most important, and the ones whose overlapping total ranges allow a rather precise age determination, are *Globorotalia velascoensis* (Cushman) and *Globorotalia aragonensis* Nuttall. *G. velascoensis* was described by Cushman from the Velasco shale of the Tampico Embayment region of Mexico. *G. aragonensis* was described by Nuttall from the Aragon formation of Mexico. Since their first description, both species have been noted in the Middle East, Mediterranean, Gulf of Mexico and Caribbean areas, and from seamounts in the Mid-Pacific. The range of *G. velascoensis* is possibly uppermost Cretaceous, definitely Paleocene, and probably lower Eocene. *G. aragonensis* is a restricted lower Eocene to middle Eocene form. The fact that these two forms are found together in an apparently uncontaminated fauna (in one crack filling) places the age of the fauna at about the boundary between the Paleocene (Midway) and the Eocene (Wilcox). The remainder of the planktonic species, from cracks and pockets, tend to favor an age dating just into the earliest Eocene, although it is uncertain whether all the listed species lived at the same time.

The nearest affinity of this Sylvania Eocene fauna is with the fossil planktonic species of the Mid-Pacific Mountains to the east (Hamilton, 1953). In the Mid-Pacific Mountains, planktonic Foraminifera of Paleocene and Eocene age occur on the tops of four flat-topped seamounts. On Horizon Guyot almost the identical fauna (as noted above for Sylvania) occurs in the cracks of manganese-coated volcanic rocks. Other than the Mid-Pacific faunas, the nearest faunal affinity of the Eocene Sylvania species is with those of the Paleocene and Eocene deposits of the Tampico Embayment region of Mexico.

MID-PACIFIC STATION 43 D

The fossil planktonic fauna from the pocket within the altered basalt of MP 43 D is correlated with the *Globigerinatella insueta* zone of the Carribbean area on the basis of the ranges of the contained species. The *G. insueta* zone was originally placed in the lower part of the upper Oligocene of the Caribbean area (for example, Stainforth, 1948a, and 1948b), but recent work both in Europe and in the Caribbean area (Kugler, 1954; Akers, 1955; Drooger, 1956; Akers and Drooger, 1957; Blow, 1957; and Bolli, 1957) indicate that this zone is in the lower to middle Miocene of the Caribbean.

The appearance in the Sylvania Guyot fauna of *Globigerinoides bispherica* Todd and *G. subquadrata* Bronnimann is of particular interest. These two species were recently named by Todd and Bronnimann (*in* Todd and others, 1954); they occur in the Miocene of the Caribbean region and in deposits on Saipan, and *G. bispherica* has been noted in the Mediterranean area (Drooger, 1956). The chances of finding these species in a single rock from a haul of dredged material on the top of a seamount are such that their discovery in this areally intermediate location is almost more than hoped for (Todd and others 1954, p. 679). The discovery of these two index species on Saipan extended the usefulness of the *Globigerinatella insueta* zone of the Caribbean area into the central Pacific; their discovery on Sylvania Guyot and in the Mediterranean (Drooger, 1956) emphasizes the importance of the species of this zone in worldwide correlations.

MID-PACIFIC STATION 43 DD

The fossil planktonic fauna from the manganese-coated calcium carbonate material obtained in dredge haul MP 43 DD is correlated with the late Miocene on the basis of the overlapping ranges of *Globigerina altispira*, *Sphaeroidinella multiloba*, *S. rutschi*, *S. seminulina*, *S. dehiscens*, and *Pulleniatina obliquiloculata* (for example see Grimsdale, 1951). M. N. Bramlette (oral communication) after an examination of the coccoliths prefers an early Pliocene dating, but adds, correctly, that the exact ranges of the coccoliths, as well as the Foraminifera, are not well enough known to state the exact age more precisely. Most species of the modern planktonic fauna had appeared by the early Miocene; therefore planktonic foraminiferal faunas younger than that must be dated on relatively few species. It appears from this study and examination of the literature (for example Phleger, Parker, and Peirson, 1953, p. 85, and Grimsdale, 1951) that the best chance to date the upper Miocene in planktonic assemblages is with the species named above and their overlap in ranges with more modern elements of the fauna such as *S. dehiscens*, and *P. obliquiloculata*.

SIGNIFICANCE OF THE FOSSIL FAUNAS

In the central North Pacific Basin, there are now several age datings of seamounts and events. From the borings at Eniwetok Atoll (Ladd, and others, 1953; Cole, 1958), it is known that Eocene (Tertiary *b*) shallow-water calcareous deposits lie just above the olivine basalt.

At Bikini Atoll, the deep bore hole to 2,556 feet bottomed in the Oligocene (?); but in footnotes (Emery, Tracey, and Ladd, 1954, p. 83) and in the papers by Cole (1954) and Todd and Post (1954), it is noted that there is a distinct possibility that the top of the Eocene was reached. A revision of the Bikini Atoll evidence by Cole (1958), however, indicates Tertiary *e* (Aquitanian).

Cushman, Todd, and Post (1954) note the presence of Tertiary Foraminifera in a core (No. 1176) taken in the saddle between Bikini Atoll and Sylvania Guyot (fig. 255). It was supposed that these species may have been redeposited from the slopes of Bikini Atoll above, but now that older material has been found on Sylvania Guyot and Tertiary fossil material has been found at the surface in the Mid-Pacific Mountains, there is a distinct possibility that this material was in place and not redeposited.

Macdonald (*in* Emery, Tracey, and Ladd, 1954, p. 123) notes that the presence of fresh glass in the volcanic rocks on Sylvania Guyot indicates that the rocks are not older than the late Paleozoic and that they, being pyroclastic rocks, were erupted in waters much shallower than the water from which they were dredged.

The early Eocene fauna from a crack in the tuff-breccia boulder (MP 43 A) near the break in slope on top of Sylvania Guyot places the age of the flat top of the volcanic peak at not younger than earliest Eocene.

In the Mid-Pacific Mountains, about 1,000–1,500 miles to the east of the Marshall Islands, Eocene ooze was found in surficial material on the top of Horizon Guyot, and Paleocene ooze was found on the top of Hess Guyot, at or near the surface of the sediment (Hamilton, 1953, 1956). The dating of an ooze on the top of a seamount merely indicates that the surface was there at a certain time and available to receive sediment; it is definitely a "not-younger-than" type of dating and may be far from the actual time when the seamount was formed, or, in the case of the flat-topped seamounts, when the seamount was at the surface of the sea. For example: Hess Guyot in the Mid-Pacific Mountains was at the surface of the sea in the Cretaceous (Aptian to Cenomanian), but the oldest ooze collected from the surface of the flat top was laid down about 40 million years later during the late Paleocene.

At Eniwetok Atoll the sample from 2,780–2,790 feet contained the first Eocene species according to Cole, so that there is about 1,900 feet of Eocene material above the basalt basement of the atoll (at about 4,600 feet). This is comparable to the Bikini Atoll bore hole, where at 2,556 feet the hole bottomed in Tertiary *e* (Aquitanian). At this point the hole was about 2,400 feet above the volcanic basement as determined by seismic techniques; if these assumptions are true then it seems likely that there is about 2,400 feet of Oligocene and Eocene (and perhaps older rock) above the basement which is about the same situation as at Eniwetok Atoll.

The finding of early Tertiary Foraminifera in the tuff-breccia on Sylvania Guyot is another block of evidence in the structure forming the geologic history of the Pacific Basin and especially the northern Marshall Islands. This new evidence fits very well into all of the other information previously reported.

The best postulated history for the Bikini Atoll–Sylvania Guyot feature is still about the same as that formulated by Emery, Tracey, and Ladd (1954, p. 126–131). The new evidence can be assimilated easily into the history, so that the events might have been somewhat as follows:

The Bikini Atoll–Sylvania Guyot feature was a twin-peaked volcanic mass (Raitt, 1954) in Late Cretaceous or earliest Tertiary time. Sylvania Guyot, the older peak, had been eroded to a bank, and possibly corals had begun to grow and form banks among the erosional debris, much of which was pyroclastic. The marginal ridges around parts of Sylvania Guyot could thus be explained; a similar marginal ridge was noted on Hess Guyot (Hamilton, 1956, p. 15) but only 1 dredge haul out of 6 on Hess Guyot contained reef coral. Bikini Atoll at this time was younger and higher and had been relatively little eroded. Subsidence in Late Cretaceous or early Tertiary time was too fast to permit coral to continue to stay at the surface (which is the favored hypothesis for the sunken, coral-bearing guyots of the Mid-Pacific Mountains). This would have left Bikini Atoll at or above the surface while Sylvania Guyot was a relatively deeply submerged bank—too deep for coral growth and below the depth of profuse bottom life. Subsequent submergence must have been relatively slow because a great reef probably began to grow on the foundation of Bikini Atoll in early Tertiary time while, at the same time, planktonic Foraminifera were being deposited in the cracks of the pyroclastic rocks on Sylvania Guyot. Nonaccumulation of sediment around the rims of Sylvania Guyot and in the saddle between Sylvania Guyot and Bikini Atoll left old rocks and sediment deposits at the seamount surface, some of which became phosphatized. This is, in general, the same situation as in the Mid-Pacific Mountains.

After the start of deposition on Sylvania Guyot in the early Tertiary one might expect to find later deposits clear through the Tertiary to Recent time. The Miocene faunas are not, therefore, unexpected.

It may be very significant in the geologic history of the north-central Pacific Basin that roughly the same events were transpiring at about the same time in the Bikini Atoll–Sylvania Guyot area, in the Mid-Pacific Mountains to the east, and at Eniwetok Atoll to the west.

SYSTEMATIC DESCRIPTIONS

The bulk of the material will be deposited in the U. S. National Museum, Washington, D. C.

Family GLOBIGERINIDAE

Genus GLOBIGERINA d'Orbigny, 1826

Globigerina altispira Cushman and Jarvis, 1936[5]

Plate 254, figures 1–3

Globigerina altispira Cushman and Jarvis, 1936, Cushman Lab Foram. Res., Contr., v. 12, p. 5, pl. 1, figs. 13, 14.

This species has been reported from the Miocene of Jamaica and Haiti, and from the upper Oligocene and Miocene of the Dominican Republic. Grimsdale (1951) reports the species from the Middle East, and it was reported as rare in a mixed-fauna core from the Mid-Pacific Mountains. Phleger, Parker, and Peirson report this species in Miocene ooze from the Atlantic. This distinctive species appears to be a worldwide index fossil of some importance; it is common in the Miocene material from MP 43 DD.

Globigerina apertura Cushman, 1918

Plate 252, figure 7

Globigerina apertura Cushman, 1918, U. S. Geol. Survey Bull. 676, p. 57, pl. 12, fig. 8.

This species has been reported from the Eocene to the Pleistocene of North America and from the Eocene faunas of the Mid-Pacific Mountains. It is rare in the MP 43 A material.

Globigerina bulloides d'Orbigny, 1826[6]

Plate 253, figure 14

Globigerina bulloides d'Orbigny, 1826, Annals Sci. Naturelles, v. 7, p. 277, no. 1; Modèles no. 76 and young, no. 17.

Phleger and Parker, 1951, Geol. Soc. America Mem. 46, p. 34, pl. 19, figs. 6, 7.

A few forms referred to this species (as diagnosed from comparison with modern forms such as those of the second citation) occur in the material from MP 43 D.

Globigerina ciperoensis Bolli, 1954

Plate 253, figures 23, 24

Globigerina ciperoensis Bolli, 1954, Cushman Found. Foram. Res. Contr., v. 5, p. 1, figs. 3, 4, 5, and 6.

Globigerina cf. *G. concinna* Reuss. Cushman and Stainforth, 1945, Cushman Lab. Foram. Res. Spec. Pub. 14, p. 67, pl. 13, fig. 1.

Bolli considers that the lower Oligocene form sometimes referred to as *G. concinna* Reuss is sufficiently distinctive to merit a new species name. This form is common in the material from MP 43 D.

Globigerina aff. G. collactea (Finlay), 1939

Globorotalia collactea Finlay, 1909, New Zealand Royal Soc. Trans. v. 69, pt. 3, p. 327, pl. 29, figs. 164, 165.

A few forms which appear to be close to *G. collactea* (Finlay) occur in the MP 43 A fauna.

Globigerina dissimilis Cushman and Bermudez, 1937

Plate 253, figures 9, 10

Globigerina dissimilis Cushman and Bermudez, 1937, Cushman Lab. Foram. Res. Contr., v. 13, p. 25, pl. 3, figs. 4–6.

A few forms referrable to this species occurred in the material from MP 43 D.

Globigerina eocaena Gümbel, 1868

Plate 252, figure 4

Globigerina eocaena Gümbel, 1868, K. Bayer. Akad. Wiss. Munchen, Math.-Physik. Cl., Abh., Munchen, Deutschland, Band 10 (1870). Abt. 2, p. 662, pl. 2, fig. 109a–b.

This species is rare in the Eocene (MP 43 A) fauna.

Globigerina mckannai White, 1928

Plate 252, figures 10, 11

Globigerina mckannai White, 1928, Jour. Paleontology, v. 2, p. 194, pl. 27, fig. 16.

This species is rare in the Sylvania Guyot fauna (MP 43 A). It was common in the Eocene fauna from Horizon Guyot.

Globigerina orbiformis Cole, 1927

Plate 252, figure 6

Globigerina orbiformis Cole, 1927, Am. Paleontology Bull., v. 14, no. 51, p. 33, pl. 5, fig. 7.

This species is rare in the Sylvania fauna from MP 43 A as it was, also, in the Eocene material from Horizon Guyot.

Globigerina ouachitaensis Howe and Wallace var. senilis Bandy, 1949

Plate 253, figure 4

Globigerina ouachitaensis senilis Bandy, 1949, Am. Paleontology Bull., v. 32, p. 121, pl. 22, fig. 5.

This variety occurs in the Eocene and middle Oligocene of the gulf coastal area and was found in the Eocene material from Horizon Guyot. It is rare in the material of MP 43 D.

Globigerina pseudobulloides Plummer, 1926

Plate 252, figure 3

Globigerina pseudobulloides Plummer, 1926, Texas Univ. Bull. 2644, p. 133, pl. 8, figs. 9a–c.

This species is common in Paleocene deposits around the world and is recorded by Nuttall from the Eocene of Mexico. It is rare in the MP 43 A material. In the Paleocene ooze from Hess Guyot this form was common.

Globigerina rotundata d'Orbigny var. jacksonensis Bandy, 1949

Plate 252, figure 1

Globigerina rotundata jacksonensis Bandy, 1949, Am. Paleontology Bull., v. 32, no. 131, p. 121, pl. 23, figs. 6a–c.

This form is rare in the Sylvania Guyot faunas.

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[5] Genus should be *Globoquadrina*.

[6] Reidentified as *Globorotalia obesa* Bolli, 1957.

Globigerina topilensis Cushman, 1925

Plate 252, figures 17, 21

Globigerina topilensis Cushman, 1925, Cushman Lab. Foram. Res., Contr., v. 1, p. 7, pl. 1, fig. 9.

Sylvania forms which appear to fall into this species are common in the crack fillings of the tuff-breccia of MP 43 A.

Globigerina triloculinoides Plummer, 1926

Plate 252, figure 2

Globigerina triloculinoides Plummer, 1926, Texas Univ. Bull. 2644, p. 134, pl. 8, figs. 10a–c.

This Danian to lower Eocene species is rare in the fossil fauna from Sylvania guyot (MP 43 A). It was common in the Mid-Pacific Mountains faunas.

Globigerina venezuelana Hedberg, 1937

Plate 253, figures 15, 16

Globigerina venezuelana Hedberg, 1937, Jour. Paleontology, v. 11, p. 681, pl. 92, fig. 7.

This species is recorded from the upper Eocene to the middle Miocene. It is common in the material from MP 43 D.

Genus GLOBIGERINOIDES Cushman, 1927

Globigerinoides bispherica Todd

Plate 253, figures 11–13

Globigerinoides bishperica Todd, 1954, Am. Jour. Sci., v. 252, p. 681, pl. 1, 4.

This species, described from the "upper Oligocene" of Saipan is also a common form in the Mediterranean area and in the *Globigerinatella insueta* zone of the Caribbean. This form, and that of *G. subquadrata* Bronnimann, may well prove to be extremely important index fossils for the lower Miocene now that worldwide distribution is shown.

Globigerinoides rubra (d'Orbigny), 1839

Plate 253, figure 5

Globigerina rubra d'Orbigny, 1839, *in* de la Sagra, Histoire Phys. Pol. Nat. Cuba, p. 82, pl. 4, figs. 12–14.

This abundant Recent form is sparsely represented in the material from MP 43 D; it is common in the late Miocene ooze (MP 43 DD).

Globigerinoides sacculifera (Brady), 1877

Plate 253, figures 3, 20–22

Globigerina sacculifera Brady, 1877, Geol. Mag., v. 4, p. 535.
Brady, 1884, Dept. Sci. Results Voyage H. M. S. *Challenger*, Zool., v. 9, p. 604, pl. 80, fig. 4.

This species is common in the material from MP 43 D and in the upper Miocene fauna from MP 43 DD.

Globigerinoides sacculifera var. fistulosa (Schubert), 1910

Plate 254, figure 14

Globigerina fistulosa Schubert, 1910, K. k. geol. Reichsanstalt Verh., no. 14, p. 324 (7), fig. 2 (in text).
Schubert, 1911, K. k. geol. Reichsanstalt Abh., Band 20, pt. 4, p. 100, figs. 132–c (in text).

This form, described from the Tertiary of New Guinea, is common in the upper Miocene material from MP 43 DD.

Globigerinoides subquadrata Bronnimann, 1954

Plate 253, figures 6–8

Globigerinoides subquadrata Bronnimann, 1954, Am. Jour. Sci., v. 525, p. 680, pl. 1, figs. 5, 8.

This species is abundant in the "upper Oligocene" of Saipan (Todd and others 1954) and is known from the Miocene of Trinidad and Venezuela. The form is common in the material from MP 43 D.

Globigerinoides triloba (Reuss), 1850

Plate 253, figures 17–19

Globigerina triloba Reuss, 1850, K. Akad. Wiss. Wien, Math.-Nat. Cl. 1., Denkschr., Wien, Osterreich, Band 1, p. 374, pl. 47, fig. 11.

This form is common in the material from MP 43 D.

Genus ORBULINA d'Orbigny, 1839

Orbulina bilobata (d'Orbigny), 1846

Plate 254, figure 11

Globigerina bilobata d'Orbigny, 1846, Foraminifères fossiles du bassin tertiare de Vienne, Gide et Comp., Paris, France, p. 164, pl. 9, figs. 11–14.

This form is rare in the upper Miocene material from MP 43 DD.

Genus SPHAEROIDINELLA Cushman, 1927

Sphaeroidinella multiloba LeRoy, 1944

Plate 254, figure 7

Sphaeroidinella multiloba LeRoy, 1944, Colorado School Mines Quart., v. 39, p. 91, pl. 4, figs. 7–9.

A form which is tentatively assigned to this species is common in the Miocene material from MP 43 DD. As noted by the writer (Hamilton, 1953, p. 228) and Miss Frances L. Parker (*in* Phleger, Parker, and Peirson, 1953, p. 18) this species, *S. rutschi*, and *S. seminulina* may well be variations of a single species (especially true of *S. seminulina* and *S. rutschi*). In 1952 Hamilton examined topotype material of specimens of *S. rutschi* and *S. seminulina* sent to Miss Parker by the U. S. National Museum. In Miss Parker's opinion and in that of Hamilton, the two species (in the material at hand) were the same, with the possible exception that the wall of *S. seminulina* appeared to be thinner and more translucent and had a round pore structure which appeared as white dots, whereas *S. rutschi* had the typical hexagonal pore structure of the Globigerinidae and a thicker, whiter wall. All these forms are important worldwide index species of the Upper Tertiary and fortunately have about the same reported range: *S. multiloba* from the lower to upper Miocene, *S. seminulina* from the upper Oligocene to the lower Pliocene, and *S. rutschi* from the middle Oligocene to the middle Miocene.

Sphaeroidinella rutschi Cushman and Renz, 1941

Plate 254, figure 6

Sphaeroidinella rutschi Cushman and Renz, 1941, Cushman Lab. Foram. Res., Contr., v. 17, p. 25, pl. 4, figs. 5a-c.

A few forms assigned to this species were noted in the Miocene material from MP 43 DD. See also the remarks under *S. multiloba* LeRoy.

Sphaeroidinella seminulina (Schwager), 1866

Plate 254, figures 4, 5

Globigerina seminulina Schwager, 1866, Novara. Exped., Geol. Theil, v. 2, p. 256, pl. 7, fig. 112.

This form occurs commonly in the Miocene material from MP 43 DD. For further remarks see the note under *S. multiloba*.

Family GLOBOROTALIIDAE

Genus GLOBOROTALIA Cushman, 1927

Globorotalia aragonensis Nuttall, 1930

Plate 252, figures 14–16

Globorotalia aragonensis Nuttall, 1930, Jour. Paleontology, v. 4, p. 288, pl. 24, figs. 6–8, 10, 11.

This species is a worldwide index fossil for the early and middle Eocene; it has been reported from the Middle East, the gulf coast area, the Caribbean area, and the Mid-Pacific flat-topped seamounts. It is common in the Sylvania guyot fauna and occurs in the same indurated crack filling (pl. 251) as *G. velascoensis* (Cushman). The overlapping range of this species with that of *G. velascoensis* places the age of the fauna as at about the boundary between the Paleocene and the Eocene.

Globorotalia centralis Cushman and Bermudez, 1937

Globorotalia centralis Cushman and Bermudez, 1937, Cushman Lab. Foram. Res., Contr., v. 13, p. 26, pl. 2, figs. 62–65.

Three specimens of this form were found in the MP 43 A material.

Globorotalia crassata (Cushman)

Plate 252, figure 5

Pulvinulina crassata Cushman, 1925, Am. Assoc. Petroleum Geologists Bull., v. 9, p. 300, pl. 7, fig. 4.

Globorotalia crassata (Cushman). Cole, 1927, Am. Paleontology Bull., v. 14, no. 51, p. 34, pl. 1, figs. 7–8.

Cushman, 1939, Cushman Lab. Foram, Res., Contr., v. 15, p. 74, pl. 12, fig. 19.

In connection with the Mid-Pacific material, plesiotype material of the last named citation was obtained from the U. S. National Museum and compared to the Mid-Pacific material. The species, as so diagnosed, is common in the Paleocene and Eocene faunas of the Mid-Pacific Mountains and is common in the Sylvania guyot material. The original figure by Cushman is entirely inadequate to identify this species.

Globorotalia crassata densa (Cushman)

Plate 252, figures 8,9

Pulvinulina crassata densa (Cushman), 1925, Am., Assoc. Petroleum Geologists Bull., v. 9, p. 301, no fig.

Globorotalia crassata densa (Cushman), 1939, Cushman Lab. Foram. Res., Contr., v. 15, p. 74, pl. 12, fig. 20.

Plesiotype material from the last-named citation was obtained from the U. S. National Museum for comparison with the Mid-Pacific material. The variety is common in the Mid-Pacific guyot faunas and is common in the Sylvania guyot material from MP 43 A.

Globorotalia membranacea (Ehrenberg), 1854

Plate 252, figure 13

Planulina membranacea Ehrenberg, 1854, Mikrogeologie, pl. 25, 1A, fig. 41, pl. 26, fig. 43.

One specimen of this Paleocene species was found in the Sylvania guyot material from MP 43 A.

Globorotalia menardii (d'Orbigny) var. fijiensis Cushman, 1934

Plate 254, figure 13

Globorotalia menardii fijiensis Cushman, 1934, B. P. Bishop Mus. Bull. 119, p. 136, pl. 17, fig. 5.

This form, named from the Tertiary of Suva, is rare in the Miocene material from MP 43DD.

Globorotalia menardii (d'Orbigny) var. multicamerata Cushman and Jarvis, 1930

Plate 254, figure 12

Globorotalia menardii multicamerata Cushman and Jarvis, 1930, Jour. Paleontology, v. 4, p. 367, pl. 34, fig. 8.

This form, named from the Miocene of Jamaica, is rare in the Miocene material from MP 43DD. It was reported by Phleger, Parker, and Peirson (1953, p. 20) from the Miocene of deep-sea cores in the Atlantic. Its geographic range is now extended to the Pacific. As noted by Phleger, Parker, and Peirson, only one report has been made from the Recent. If this occurrence in deep water off Cuba is the result of transported material, then the form might be useful in dating the upper Tertiary.

Globorotalia tumida (Brady) cf. G. tumida var. flexuosa (Koch), 1923

Plate 254, figures 8–10

Pulvinulina flexuosa Koch, 1923, Eclogae Geol. Helv., Lausanne, Suisse, v. 18, p. 357, p. 351, tfs., 9a–b, 10a–b.

The form illustrated may be compared to the variety, but further study is needed to differentiate the *menardii*-

tumida complex. It is probable that close study of this group will yield species and varieties of stratigraphic importance, especially from the upper Miocene to the Recent where such markers are sorely needed.

Globorotalia velascoensis (Cushman), 1925

Plate 252, figures 18–20

Pulvinulina velascoensis Cushman, 1925, Cushman Lab. Foram. Res., Contr. v. 1, p. 19, pl. 3, figs. 5a–c.
Globorotalia velascoensis (Cushman), 1927, Jour. Paleontology, v. 1, pl. 27, figs. 7–9.

This species is the best worldwide index fossil for the lower Tertiary. It has been noted in material from the Middle East, the gulf coast area, Caribbean area, and the Mid-Pacific Mountains. Its geologic range is possibly uppermost Cretaceous, definitely Paleocene, and probably lower Eocene. The form noted in the Sylvania guyot material is very close to the type; it has the distinctive beaded and raised sutures on the dorsal side, as well as the open umbilicus.

Globorotalia whitei Weiss, 1955

Plate 253, figures 1, 2

Globigerina crassaformis Galloway and Wissler. White, 1928, Jour. Paleontology, v. 2, p. 193, pl. 27, fig. 14.
Globorotalia crassaformis (Galloway and Wissler). Nuttall, 1935, Jour. Paleontology, v. 9, p. 130, pl. 15, figs. 21, 29.
Globorotalia whitei Weiss, 1955, Jour. Paleontology, v. 29, p. 18, pl. 6, figs. 1–3.

This new species, as diagnosed by Weiss, is known from the Paleocene and lower Eocene of Peru, the Upper Cretaceous and Paleocene of Mexico, and the Eocene of Venezuela. This species is rare in the lowermost Eocene fauna from Sylvania guyot, but this new locality indicates a widespread distribution. Specimens from the Sylvania guyot fauna were sent to Weiss, who affirmed that they were identical with his type material.

Globorotalia wilcoxensis Cushman, 1932

Plate 252, figure 12

Globorotalia wilcoxensis Cushman and Ponton, 1932, Cushman Lab. Foram. Res., Contr. v. 8, p. 71, pl. 9, fig. 10.

This form is rare in the Sylvania material.

SELECTED BIBLIOGRAPHY

Akers, W. H., 1955, Some planktonic Foraminifera of the American gulf coast and suggested correlations with the Caribbean Tertiary: Jour. Paleontology, v. 29, p. 647–664.

Akers, W. H., and Drooger, C. W., 1957, Miogypsinids, planktonic Foraminifera, and gulf coast Oligocene-Miocene correlations: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 656–678.

Arrhenius, G., Bramlette, M. N., and Picciotto, E., 1957, Localization of radioactive and stable heavy nuclides in ocean sediments: Nature, v. 180, p. 85–86.

Blow, W. H., 1957, Transatlantic correlation of Miocene sediments: Micropaleontology, v. 3, p. 77–79.

Bolli, H. M., 1957, Planktonic Foraminifera from the Oligocene-Miocene Cipero-Lengua formations of Trinidad: U. S. Natl. Mus. Bull. 215.

Buser, W. and Grütter, A., 1956, Uber die Natur der Mangan-knollen, Schweiz: Mineralogische und Petrographische Mitteilungen, v. 36, p. 49–62.

Clark, J. S., 1955, Solubility criteria for the existence of hydroxyapatite: Canadian Jour. Chemistry, v. 33, p. 1696–1700.

Clark, J. S., and Turner, R. C., 1955, Reactions between solid calcium carbonate and orthophosphate solutions: Canadian Jour. Chemistry, v. 33, p. 665–671.

Cole, W. S., 1954, Larger Foraminifera and smaller diagnostic Foraminifera from Bikini drill holes: U. S. Geol. Survey Prof. Paper 260–O.

——— 1958, Larger Foraminifera from Eniwetok drill holes: U. S. Geol. Survey Prof. Paper 260–V.

Cushman, J. H., Todd, Ruth, and Post, R. J., 1954, Recent Foraminifera of the Marshall Islands: U. S. Geol. Survey Prof. Paper 260–H.

Dietz, R. S., Emery, K. O., and Shepard, F. P., 1942, Phosphorite deposits on the sea floor off southern California: Geol. Soc. America Bull., v. 53, p. 815–848.

Drooger, C. W., 1956, Transatlantic correlation of the Oligo-Miocene by means of Foraminifera: Micropaleontology, v. 2, p. 183–192.

Emery, K. O., Tracey, J. I., Jr., and Ladd, H. S., 1954, Geology of Bikini and nearby atolls, Pt. 1, Geology: U. S. Geol. Survey Prof. Paper 260–A.

Glaessner, M. F., 1945, Principles of micropaleontology, Oxford Univ. Press, London.

Goldberg, E. D., 1954, Marine geochemistry I. Chemical scavengers of the sea: Jour. Geology, v. 62, 249–265.

Grimsdale, T. F., 1951, Correlation, age determination, and the Tertiary pelagic Foraminifera: Proc. Third World Petroleum Cong., sec. 1, p. 463–472.

Hamilton, E. L., 1953, Upper Cretaceous, Tertiary, and Recent planktonic Foraminifera from Mid-Pacific flat-topped seamounts: Jour. Paleontology, v. 27, p. 204–237.

——— 1956, Sunken islands of the Mid-Pacific Mountains: Geol. Soc. America Mem. 64.

Henson, F. R. S., 1938, Stratigraphical correlation by small Foraminifera in Palestine and adjoining countries: Geol. Mag. v. 75, p. 227–233.

Kugler, H. G., 1954, The Miocene-Oligocene boundary in the Caribbean region: Geol. Mag., v. 91, p. 410–414.

Ladd, H. S., and others, 1953, Drilling on Eniwetok Atoll, Marshall Islands: Am. Assoc. Petroleum Geologists Bull., v. 37, p. 2257–2280.

McConnell, D. M., 1938, A structural investigation of the isomorphism of the apatite group: Am. Mineralogist, v. 23, p. 1–19.

Phleger, F. B, Parker, F. L., and Peirson, J. F., 1953, North Atlantic Foraminifera: Repts Swedish Deep-Sea Exped., v. 7, no. 1

Raitt, R. W., 1954, Seismic refraction studies at Bikini and Kwajalein Atolls and Sylvania Guyot: U. S. Geol. Survey Prof. Paper 260–K.

Reiss, Z., 1955, Micropaleontology and the Cretaceous–Tertiary boundary in Israel: Israel Res. Council Bull., Sec. B, v. 5B, p. 105–120.

Stainforth, R. M., 1948a, Applied micropaleontology in coastal Ecuador: Jour. Paleontology, v. 22, p. 113–151.

———1948b, Description, correlation, and paleoecology of Tertiary Cipero marl formation, Trinidad, B. W. I.: Am. Assoc. Petroleum Geologists Bull., v. 32, p. 1292–1330.

———1949, Foraminifera in the Upper Tertiary of Egypt: Jour. Paleontology, v. 23, p. 419–422.

Todd, Ruth, and others, 1954, Probable occurrence of Oligocene on Saipan: Am. Jour. Sci., v. 252, p. 673–682

Todd, Ruth, and Post, R. J., 1954, Smaller Foraminifera from Bikini drill holes: U. S. Geol. Survey Prof. Paper 260–N.

Tromp, S. W., 1949, The determination of the Cretaceous–Eocene boundary * * * in the Near East: Jour. Paleontology, v. 23, p. 673–676.

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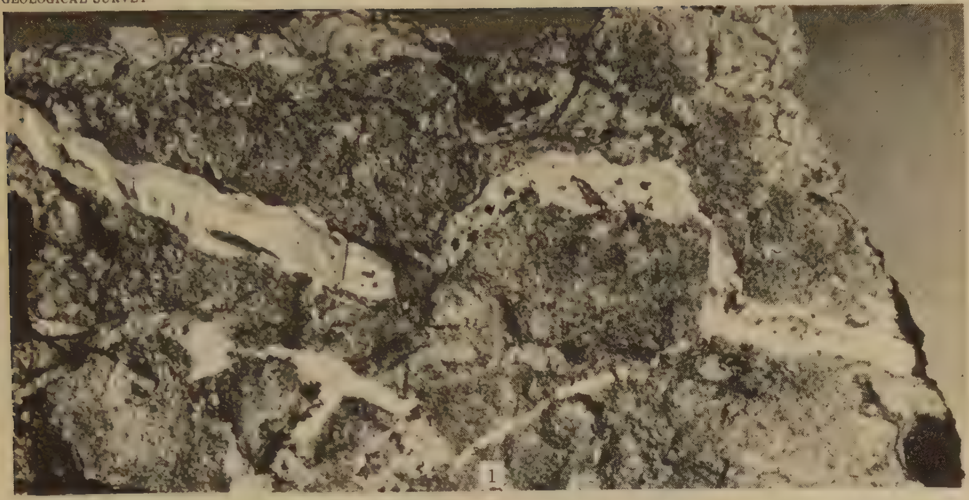
○

PLATES 250–254

PLATE 250

Figure 1. Volcanic tuff-breccia with cracks filled with white, partly phosphatized Eocene *Globigerina* ooze (MP 43 A). At the lower right, note the black crust of ferruginous oxide covering both the tuff-breccia and the crack filling. × 2.4.

2. Volcanic tuff-breccia with pockets and cracks filled, or partly filled, with partly phosphatized Eocene *Globigerina* ooze (MP 43 A). Note the pocket (lower right) containing indurated ooze and phillipsite crystals. × 3.0.



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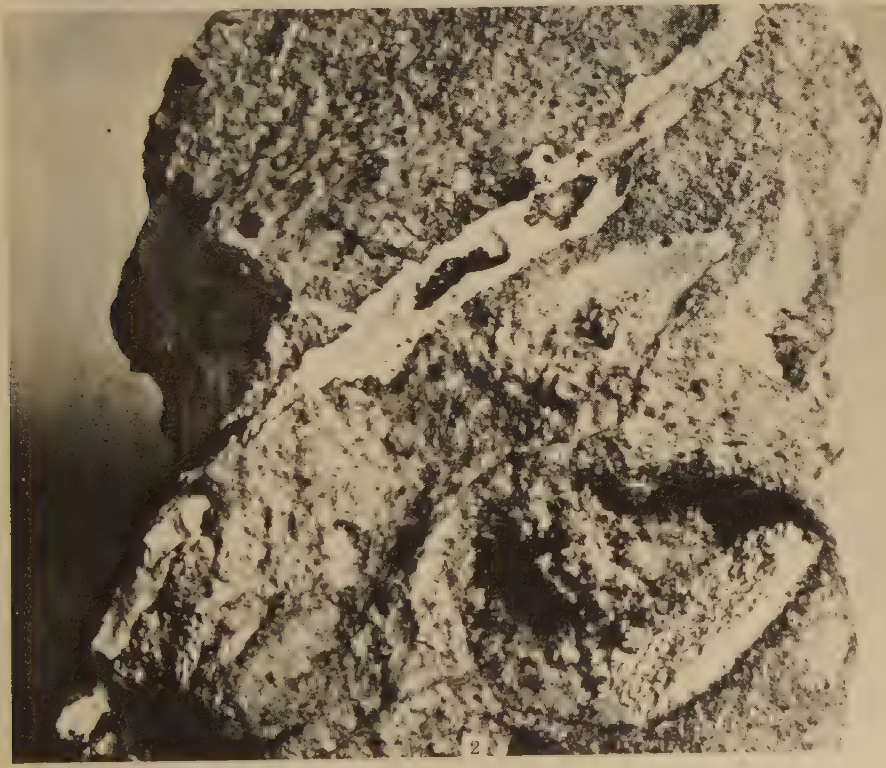

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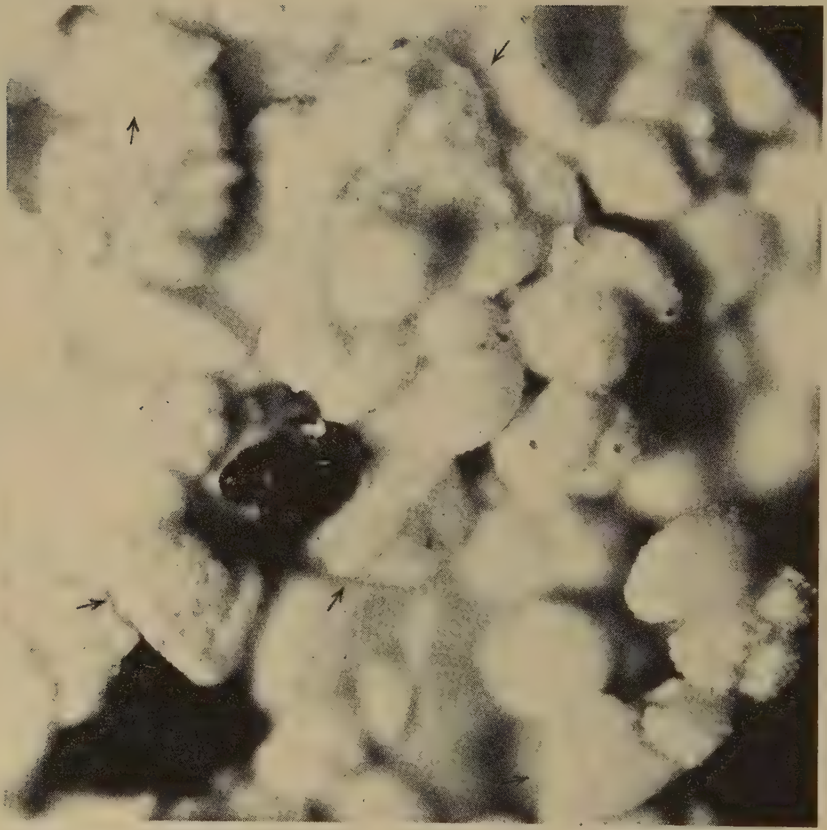
VOLCANIC TUFF-BRECCIA CONTAINING EOCENE *GLOBIGERINA* OOZE



PHOTOMICROGRAPH OF EOCENE PLANKTONIC FORAMINIFERA

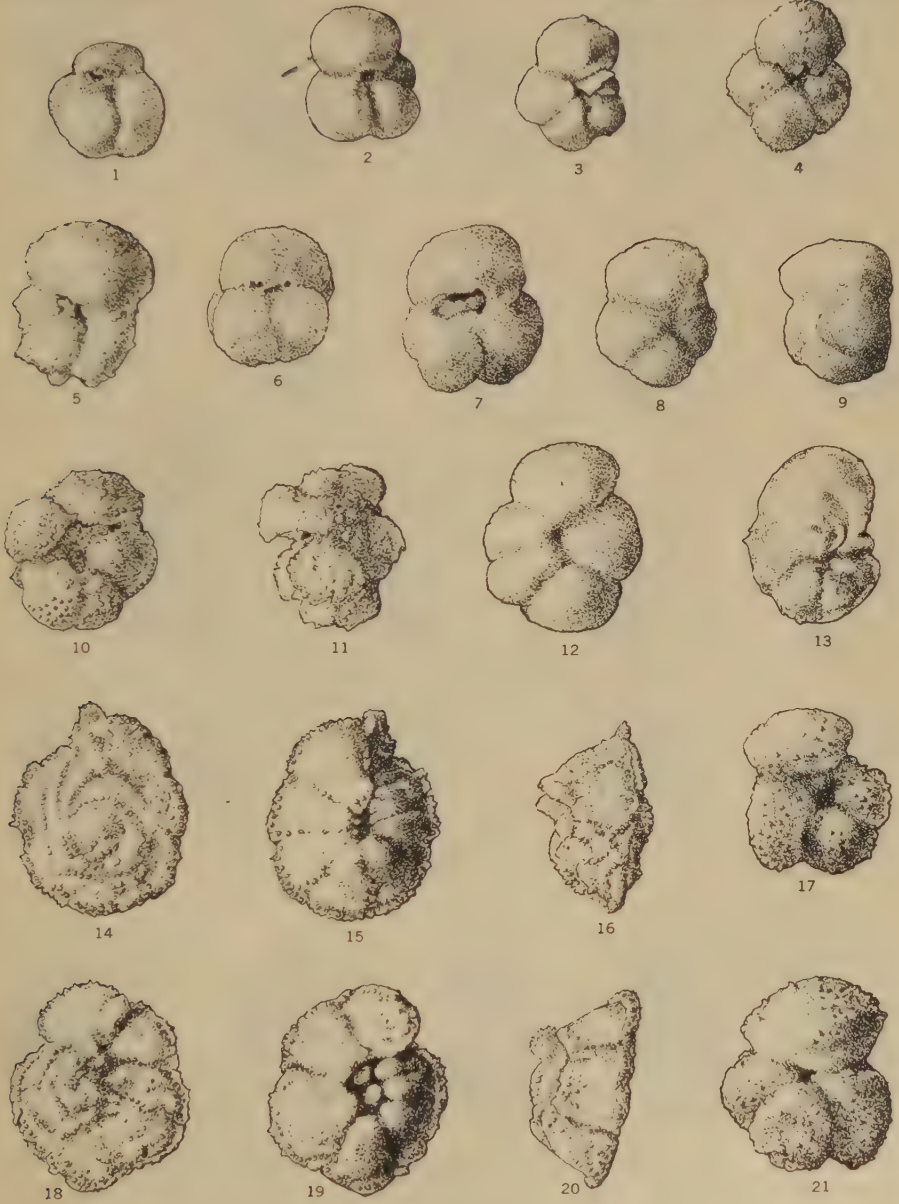
(236)

PLATE 251

Photomicrograph of Eocene planktonic Foraminifera on the top surface of an indurated, partly phosphatized *Globigerina* ooze crack filling (MP 43 A). Black material near the center is ferruginous manganese oxide. Approximately × 60. Keeled *Globorotalia*, typical of lower Tertiary faunas, are indicated by arrows.

PLATE 252

FIGURE 1. *Globigerina rotundata* d'Orbigny var. *jacksonensis* Bandy. × 50 (p. 791).
2. *Globigerina triloculinoides* Plummer. × 66 (p. 792).
3. *Globigerina pseudobulloides* Plummer. × 82 (p. 791).
4. *Globigerina eocaena* Gümbel. × 85 (p. 791).
5. *Globorotalia crassata* (Cushman). × 74 (p. 793).
6. *Globigerina orbiformis* Cole. × 53 (p. 791).
7. *Globigerina apertura* Cushman. × 76 (p. 791).
8, 9. *Globorotalia crassata densa* (Cushman). × 64 (p. 793).
8, ventral view; 9, peripheral view.
10, 11. *Globigerina mckannai* White. × 58 (p. 791).
10, ventral view; 11, peripheral view.
12. *Globorotalia wilcoxensis* Cushman and Ponton. × 56 (p. 794).
13. *Globorotalia membranacea* (Ehrenberg). × 79 (p. 793).
14, 15, 16. *Globorotalia aragonensis* Nuttall. × 55 (p. 793).
14, dorsal view; 15, ventral view; 16, peripheral view.
17, 21. *Globigerina topilensis* Cushman. (p. 792).
17, × 21; 21, × 60.
18, 19, 20. *Globorotalia velascoensis* (Cushman). × 54 (p. 794).
18, dorsal view; 19, ventral view; 20, peripheral view.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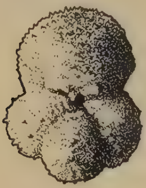
LOWER EOCENE PLANKTONIC FAUNA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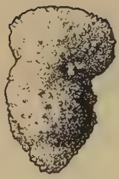
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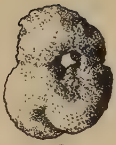
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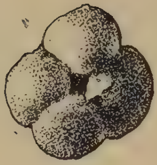
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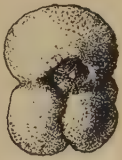
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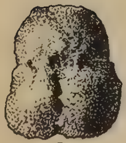
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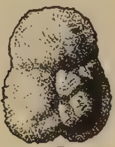
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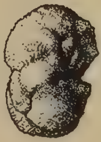
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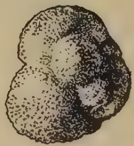
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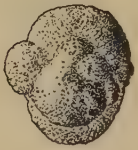
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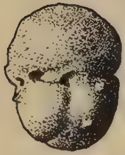
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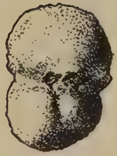
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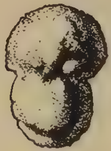
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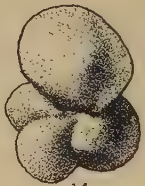
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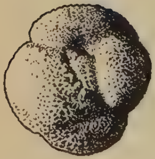
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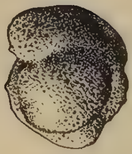
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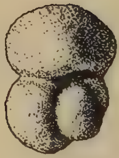
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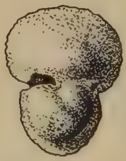
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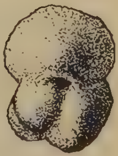
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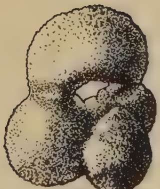
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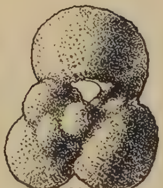
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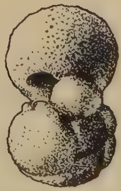
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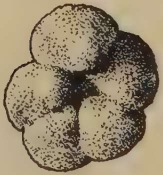
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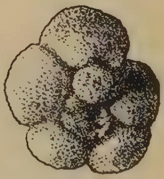
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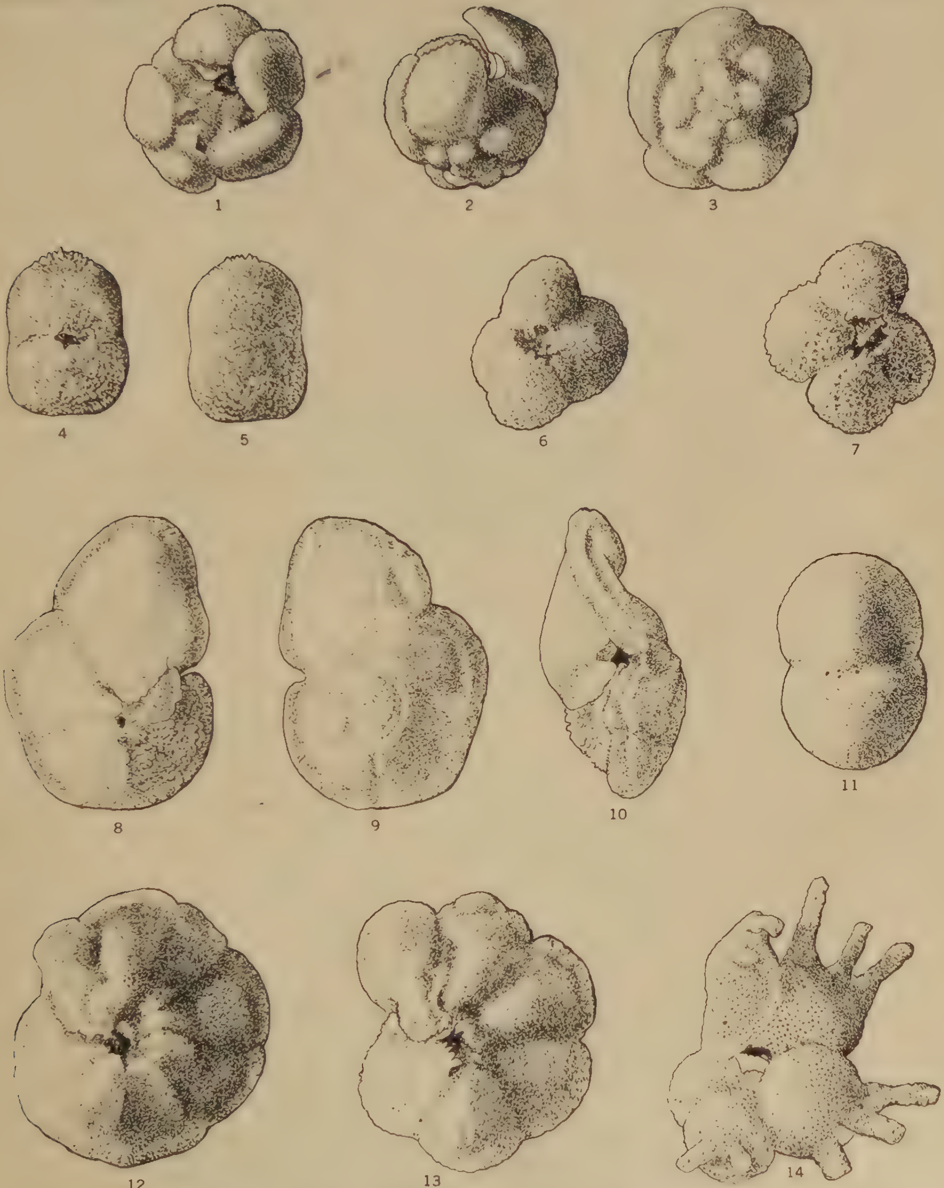
MIOCENE AND LOWER EOCENE PLANKTONIC FAUNA

PLATE 253

FIGURES 1, 2. *Globorotalia whitei* Weiss. × 66 (p. 794). From lower Eocene fauna of MP 43 A.
1, ventral view; 2, peripheral view.
3. *Globigerinoides sacculifera* (Brady). × 75 (p. 792).
4. *Globigerina ouchitaensis* Howe and Wallace var. *senilis* Bandy. × 58 (p. 791).
5. *Globigerinoides rubra* (d'Orbigny). × 63 (p. 792).
6, 7, 8. *Globigerinoides subquadrata* Bronnimann. × 57 (p. 792).
6, ventral view; 7, dorsal view; 8, peripheral view.
9, 10. *Globigerina dissimilis* Cushman and Bermudez. × 60 (p. 791).
9, ventral view; 10, peripheral view.
11, 12, 13. *Globigerinoides bispherica* Todd. × 64 (p. 792).
11, ventral view; 12, dorsal view; 13, peripheral view.
14. *Globigerina bulloides* d'Orbigny. × 77 (p. 791).
15, 16. *Globigerina venezuelana* Hedberg. × 73 (p. 792).
15, ventral view; 16, peripheral view of another specimen.
17, 18, 19. *Globigerinoides triloba* (Reuss). × 62 (p. 792).
17, ventral views; 18, peripheral view; 19, dorsal view.
20, 21, 22. *Globigerinoides sacculifera* (Brady). × 72 (p. 792).
20, ventral view; 21, dorsal view; 22, peripheral view.
23, 24. *Globigerina ciperoensis* Bolli. × 62 (p. 791).
23, ventral view; 24, dorsal view.

PLATE 254

FIGURES 1, 2, 3. *Globigerina altispira* Cushman and Jarvis. × 60 (p. 791).
1, ventral view; 2; peripheral view; 3, dorsal view.
4, 5. *Sphaeroidinella seminulina* (Schwager.) × 66 (p. 793).
4, ventral view; 5, dorsal view.
6. *Sphaeroidinella rutschi* Cushman and Renz. × 77 (p. 793).
7. *Sphaeroidinella multiloba* LeRoy. × 65 (p. 792).
8, 9, 10. *Globorotalia tumida* (Brady) cf. *G. tumida flexuosa* (Koch). × 66 (p. 793).
8, ventral view; 9, dorsal view; 10, peripheral view.
11. *Orbulina bilobata* (d'Orbigny). × 49 (p. 792).
12. *Globorotalia menardii* (d'Orbigny) var. *multicamerata* Cushman and Jarvis. × 61 (p. 793).
13. *Globorotalia menardii* (d'Orbigny) var. *fijiensis* Cushman. × 46 (p. 793).
14. *Globigerinoides sacculifera* (Brady) var. *fistulosa* (Schubert). × 68 (p. 792).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UPPER MIOCENE PLANKTONIC FAUNA

(244)

OCEANOGRAPHIC OBSERVATIONS IN THE PANAMA BIGHT, "ASKOY" EXPEDITION, 1941

WARREN S. WOOSTER

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La Jolla, California

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INTRODUCTION

The Panama Bight may be defined as that part of the eastern tropical Pacific Ocean that lies between the Isthmus of Panama (about latitude 9° N.) on the north and Punta Santa Elena (about latitude 2° S.) on the south and that extends westward from the coasts of Panama, Colombia, and Ecuador to about longitude 81° W. As thus defined, the region lies to the north of the usual position of the Peru Current and is occupied by the warm surface waters common to tropical latitudes.

The Panama Bight is of great oceanographic interest because (1) it marks the eastward limit of waters of the Equatorial Countercurrent, (2) it is characterized by great seasonal variations in oceanographic conditions apparently related to changes in the position of the Intertropical Convergence, and (3) its waters are reputed to enter into *El Niño* phenomenon occasionally reported south of the region off the coast of northern Peru. Yet prior to 1941, only sporadic oceanographic observations had been made in the Panama Bight, usually incidental to other work of expeditions.

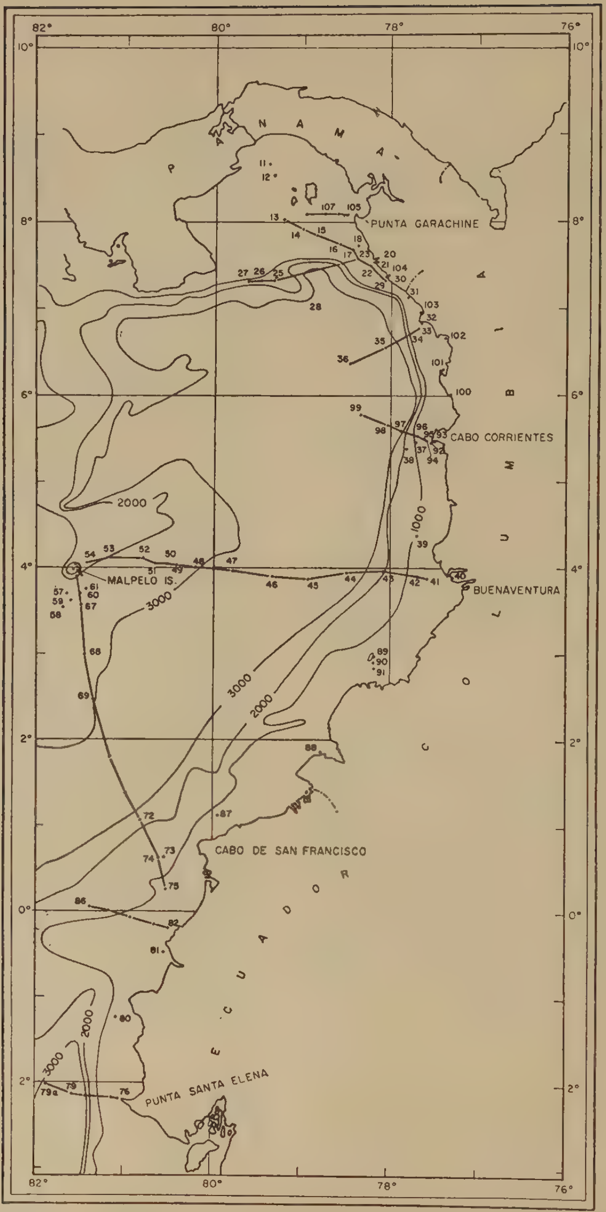
From February 9 to May 26, 1941, the American Museum of Natural History conducted an oceanographic expedition in this region aboard the diesel schooner "Askoy" under the leadership of Robert Cushman Murphy. Brief preliminary reports concerning the purpose, personnel, sponsorship, and work of the expedition have already been published (Murphy, 1941, 1942, 1944) as have descriptions of the collections of fishes (Nichols and Murphy, 1944), crabs (Garth, 1948), and marine mollusks (Hertlein and Strong, 1955).

During the "Askoy" expedition, temperature and salinity observations were made on about 80 stations (fig. 1) to depths of 125 meters or less. Most subsurface temperature measurements were made with the bathythermograph (Spilhaus, 1938), one of the first uses of this instrument in the Pacific; a few were made with reversing thermometers. Salinity samples were collected and subsequently analyzed at the Woods Hole Oceanographic Institution. The analysis of the "Askoy" data forms the basis of this paper.

As the "Askoy" observations were only exploratory and were made during a relatively brief period of time, they do not provide sufficient information to permit a definitive oceanographic study of the area. It is hoped, however, that their analysis here will facilitate further study when more data have been accumulated.

In preparing this report, I am especially indebted to Dr. Robert Cushman Murphy who made available all data from the expedition and who lent me his unpublished journal of the voyage. I am also grateful to Mr. Gunnar Roden who prepared the current charts and assisted in the analysis of other data, and to Messrs. Robert S. Arthur and Milner B. Schaefer who made many valuable suggestions. I wish also to acknowledge the stimulation afforded by many conversations with the late Townsend Cromwell whose wisdom and knowledge of the oceans meant so much to me during the years we worked together.

This work was supported in part by the Office of Naval Research, the Inter-American Tropical Tuna Commission, and the United States Fish and Wildlife Service.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CABO CORRIENTES
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MALPELO IS.
CABO DE SAN FRANCISCO
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PUNTA SANTA ELENA
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FIG. 1. Location of "Askoy" observations and generalized bathymetry of the Panama Bight (depths in meters) from sheets A'1 and A1 (1935) of the "Carte générale bathymétrique des océans" (International Hydrographic Bureau, Monaco, third edition).

(250)

PHYSICAL GEOGRAPHY OF THE PANAMA BIGHT

IN THE OPEN OCEAN the distribution of temperature and salinity near the surface is governed by advection and diffusion of heat and dissolved substances and by the exchange of energy and water between the sea surface and the atmosphere. In a coastal region such as the Panama Bight, oceanographic conditions are also influenced by the adjacent land mass and the submerged topography. Before the "Askoy" observations are discussed, therefore, it is desirable to describe briefly the physical geography of the region.

TOPOGRAPHY

Western South America, from latitude 50° S. to latitude 10° N., is dominated by the cordillera of the Andes. "There is no other mountain system in the world that possesses the combination of such length, continuity and altitude. This huge barrier rises almost from the Pacific, is 100 to 400 miles broad, and contains few passes lower than 12,000 feet for a distance of 3,500 miles" (United States Hydrographic Office, 1945).

East of the Panama Bight, the western branch of the Andes, the Cordillera Occidental, lies 30 to 100 miles inland. Between the Andes and the sea the coastal strip is relatively low, except from Cabo Corrientes north to Punta Garachiné where the Serranía del Baudó (also referred to as the Cordillera del Chocó) lies close to the coast. Although these mountains are in general less than 1000 meters high, the coast is steep, rivers are few, and most of the runoff goes into the Caribbean. Southward, between Cabo Corrientes and Cabo de San Francisco, stretches a broad forested plain. "This is the maritime Chocó, a flooded lowland of perpetual rains, of selva and morasses, of hundreds of streams, many or most of which pour into the Pacific through multiple mouths" (Murphy, 1939). South of Cabo de San Francisco the land rises, the shore becomes cliffy, and there are no large rivers until the Guayas is reached.

Bathymetric studies have shown the Panama Bight to be part of what has been termed "Panama Basin" (Shumway, 1954). This basin is enclosed by Central and South America, Cocos Ridge, the Galápagos Islands, and Carnegie Ridge (fig. 2). Cocos Ridge extends from the Galápagos Islands to Central America at a general depth of 900 to 1000 fathoms (1650 to 1830 meters). The inshore end of this ridge may be pierced by the Guatemala Trench. Carnegie Ridge is a relatively shallow sea-floor area west of Ecuador which is separated bathymetrically from the continental shelf by the northern extension of the Peru Trench (Shumway, 1954, 1957). About 7200 square miles of sea floor on the ridge lie shoaler than 800 fathoms (1460 meters), and the entire ridge appears to be shoaler than 1200 fathoms (2200 meters). There is some indication that the deep water of the basin is isolated from adjacent waters of the Pacific by these two ridges (Wooster, MS).

The deep portion of the Panama Bight may constitute a sub-basin, separated from the rest of the Panama Basin by the relatively shoal area around Malpelo Island (Jones, 1950, p. 912). A simplified picture of the bottom topography east of longitude 82° W. is shown in figure 1. Much of the basin lies deeper than 3000 meters, and between the Gulf of Panama and Punta Santa Elena the shelf is nowhere wider than 30 miles. The Gulf of Panama is a large shoal area less than 200 meters deep. The only oceanic island is Malpelo Island, a mile-long barren rock at latitude 3° 59′ N., longitude 81° 34′ W.

CLIMATOLOGY

The climatology of most regions of the world ocean is little known because of the lack of long and uninterrupted series of meteorological observations. In the Panama Bight, as in other oceanic areas, such observations are scarce, even along the coast where there are few large population centers. The discussion that follows serves only to delineate the broad features of climatological variations in the region and does not attempt to consider in detail the nature or causes of such variations.

The climatological model of general circulation in the tropics seems to apply in the least equivocal fashion to the eastern parts of oceans (Palmer, 1951). According to this model, when diurnal and seasonal perturbations of thermal and mechanical origin are omitted, one finds a system of trade winds blowing steadily from an easterly quarter towards the equator in the lower layers of the atmosphere. As the northeast and southeast trades approach one another, they become light and variable, this weakening being part of the observed horizontal velocity convergence in the two currents and the accompanying increased vertical component of the motion. At high altitudes, motion of the air is predominantly away from the equator, completing the circulation cells.

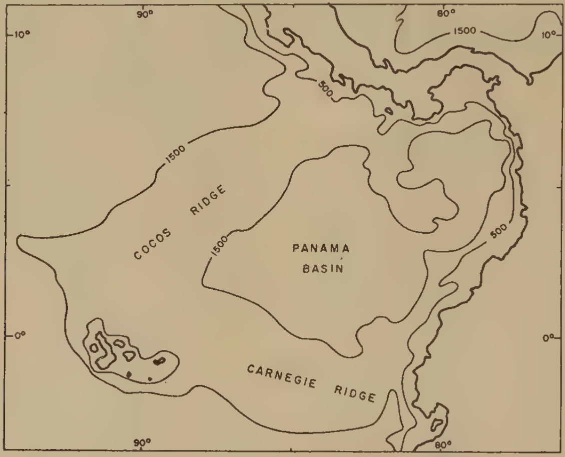


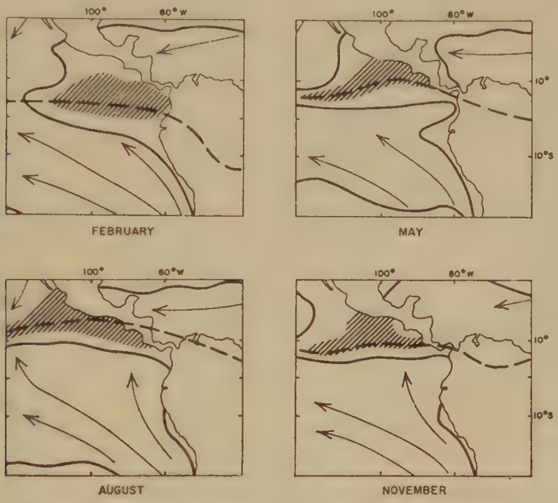
FIG. 2. Generalized bathymetry of Panama Basin (depths in fathoms), after Jones (1950) and Shumway (1953).

The region of light variable winds near the equator is called the "doldrums," and the region of convergence (in the atmosphere) located within the doldrums is often called the "Intertropical Convergence" (I.T.C.). Crowe (1952), in a statistical analysis of shipboard meteorological observations, has defined the location of the trades as those areas where 70 per cent of all winds blow from the predominant quadrant, and considers the doldrums as occurring within areas where less than 50 per cent of all winds blow from the predominant quadrant. The seasonal movement of the doldrums (as thus defined) in the eastern tropical Pacific is shown in figure 3. Within this doldrum "wedge," wind speeds have mean values no greater than 4 to 6 knots. Seasonal contrasts in weather within the Panama Bight are related to movement of the doldrum wedge and the Intertropical Convergence that lies within it.

In northern winter (January to March), the doldrums lie farthest south, covering all the Panama Bight except the Gulf of Panama. This is the dry season in Panama, when the Caribbean trades usually extend across the low lands of the Isthmus into the Gulf, or even farther south. These offshore northerlies cause upwelling within the Gulf, raising the surface salinity, lowering the surface temperature, and enriching the surface layer with subsurface nutrients (Fleming, 1940; Schaefer, Bishop, and Howard, 1958). At the same time, the Intertropical Convergence, accompanied by heavy rains, lies across the coast near the Ecuador-Colombia border, bringing the rainy season to the southern part of the Panama Bight.

In northern summer (July to September), the doldrums lie farthest north, with the Intertropical Convergence and its associated heavy rains being found north of Panama. South of Cabo de San Francisco rainfall drops off abruptly during this season. At the same time, despite the position of the Intertropical

Convergence, the central part of the Bight receives heavy rainfall. These rains cannot be considered purely orographic, as they appear to represent merely the coastal intersection of a rain belt extending westward far out into the Pacific (United States Department of Agriculture, 1938, charts 97 and 98).



FEBRUARY MAY

AUGUST NOVEMBER

FIG. 3. Average positions of the limits of trade-wind circulation (heavy solid lines), doldrums (shaded), and the Intertropical Convergence (heavy dashed lines), after Crowe (1952). Arrows indicate average direction of air flow.

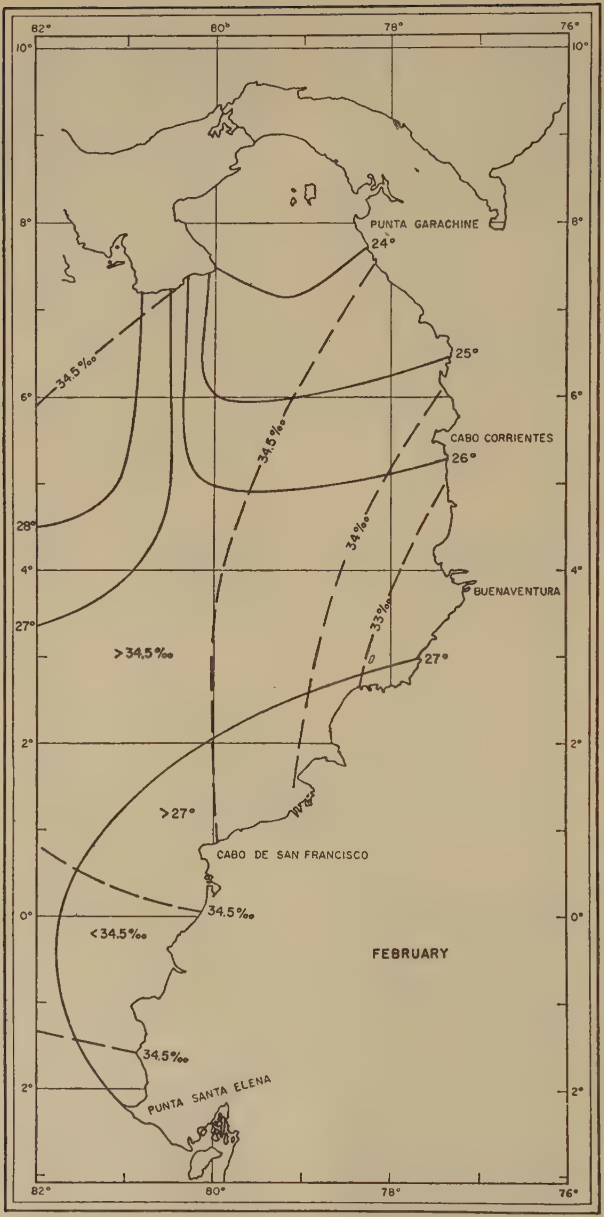
Most of the Panama Bight is dominated by southwest winds from June through November. These winds are part of the "southeast" trade-wind circulation, which in the region of the Panama Bight curves towards the northeast, roughly paralleling the coast. Although it is tempting to suggest that this curving is caused by the position of the Andes, it should be noted that the Atlantic southeast trades curve eastward in similar fashion into the Bight of Biafra in equatorial Africa where a similar mountain range does not exist (United States Department of Agriculture, 1938, charts 15 to 26). This phenomenon has been discussed by Riehl (1954, p. 8) and by Godske and his co-authors (1957, pp. 261, 493).

At any given time the local distribution of winds and precipitation may differ significantly from the mean climatological distribution discussed above. Extreme variations from the average picture probably have significant repercussions to the south of the Panama Bight, in the northern part of the Peru Current system.

Average Surface Oceanographic Conditions

A description of average surface temperature and salinity in the Pacific Ocean, based on an analysis of observations made by merchant and naval vessels, has been prepared by Schott (1935, pls. 20–28). Conditions in the Panama Bight in February and in August are shown here in figures 4 and 5 (Schott also has surface temperature charts for May and November, but does not describe the salinity distribution for those months).

In February, over most of the Panama Bight, surface temperatures of 26° to 28° C. and surface salinities of 34 to 35 parts per mille are found. Only in a small area off the coast of Colombia near Buenaventura does the salinity drop to less than 33 parts per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CABO CORRIENTES
26°
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BUENAVENTURA
33‰
27°
>34.5‰
27°
2°
2°
>27°
CABO DE SAN FRANCISCO
34.5‰
0°
0°
<34.5‰
FEBRUARY
34.5‰
2°
2°
PUNTA SANTA ELENA
82°
80°
78°
76°

FIG. 4. February average distribution of surface temperature, in degrees Centigrade (solid lines), and surface salinity, in parts per mille (dashed lines), after Schott (1935).

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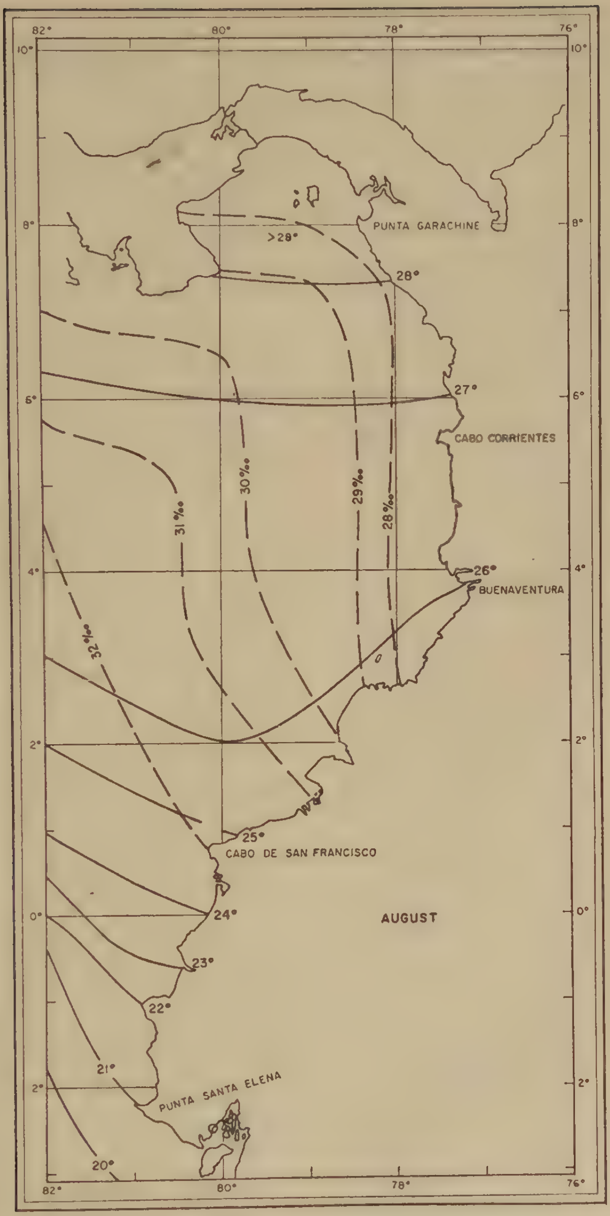
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24°
AUGUST
23°
22°
21°
PUNTA SANTA ELENA
20°

FIG. 5. August average distribution of surface temperature, in degrees Centigrade (solid lines), and surface salinity, in parts per mille (dashed lines), after Schott (1935).

mille, and temperatures lower than 26° C. occur only in the Gulf of Panama and for a hundred miles or so to the south. The relatively low surface temperatures of the Gulf are attributed to winter upwelling, as mentioned above.

By May low surface temperatures have disappeared in the Gulf, and surface waters cooler than 26° C. are found south of Cabo de San Francisco. This region of relatively cool water extends farther north in August, the isotherm of 26° C. reaching Buenaventura. The distribution of surface salinity in August is strikingly different from that of February, the whole of the Panama Bight now being covered with surface waters of low salinity (less than 33°/₀₀). Along the coast of Colombia and in the Gulf of Panama, surface salinities of less than 28 parts per mille are found, showing clearly the effect of the heavy rainfall and runoff of this season.

It is difficult to estimate how reliable these charts are as a description of surface conditions in the sea. Figures 4 and 5 represent greatly enlarged portions of Schott's original charts and are based on a small number of observations. There are not enough hydrographic stations to permit a meaningful comparison. The few winter data available show that temperatures along the shelf are comparable, but that observed salinities may be several parts per mille less than those shown by Schott. Summer data show surface salinities in the open ocean somewhat higher than those of Schott, with rather comparable values of temperature and salinity along the shelf. Although in detail the comparison between observed values and the average distributions is not very good, at least the striking difference in surface conditions between February and August as shown by Schott appears to be real.

A representation of the average surface circulation in the Panama Bight at different seasons is given in figures 6 to 9. The current vectors in these charts were determined by averaging for three-month periods the values given in "The atlas of surface currents, northeastern Pacific Ocean" (United States Hydrographic Office, 1947), weighting each monthly vector by the number of observations used in the computing of it. When 10 or fewer observations were available in a given 1-degree square during the three-month period, no average was determined. Similar values were not available for the region south of the equator. It should be remembered that these charts represent averages of ship drift observations, and the surface currents observed at any given time may be quite different from those shown by the charts.

These charts show a surface current flowing towards the north along the coast of South America north of Cabo de San Francisco during each quarter. This current appears to be weak during summer and autumn (less than 20 cm. per sec.) and somewhat stronger during winter and spring (20–30 cm. per sec.). It seems unlikely that this current carries water from the Peru Current as has been suggested (see discussion of the Colombia Current below).

Throughout the year these charts show a current towards the south (30–40 cm. per sec.) in the Gulf of Panama. The strongest currents (50 cm. per sec. or greater) in the whole area are found in the northwest corner of the Panama Bight during the winter. These currents set towards the southwest and are presumably related to the prevailing northerlies during this season. However, during all seasons the weak set in this area is in the same general direction. In the central and southern parts of the Bight, currents are quite weak (usually less than 20 cm. per sec.) except during the first three months of the year, and in general have an eastward component. West of longitude 80° W. during the winter, currents are stronger (up to 40 cm. per sec.) and have a westward component, carrying surface water out of the Bight.

In summary, these average charts suggest that the surface waters of the Panama Bight circulate in the counterclockwise sense, being fed from the west in the southern and central parts and discharging to the west in the northern part. During the winter, currents are strongest over most of the Bight, and supply from the west apparently takes place farthest south.

AVERAGE SUBSURFACE OCEANOGRAPHIC CONDITIONS

Because of the general scarcity of data, there have been few attempts to describe average subsurface conditions anywhere in

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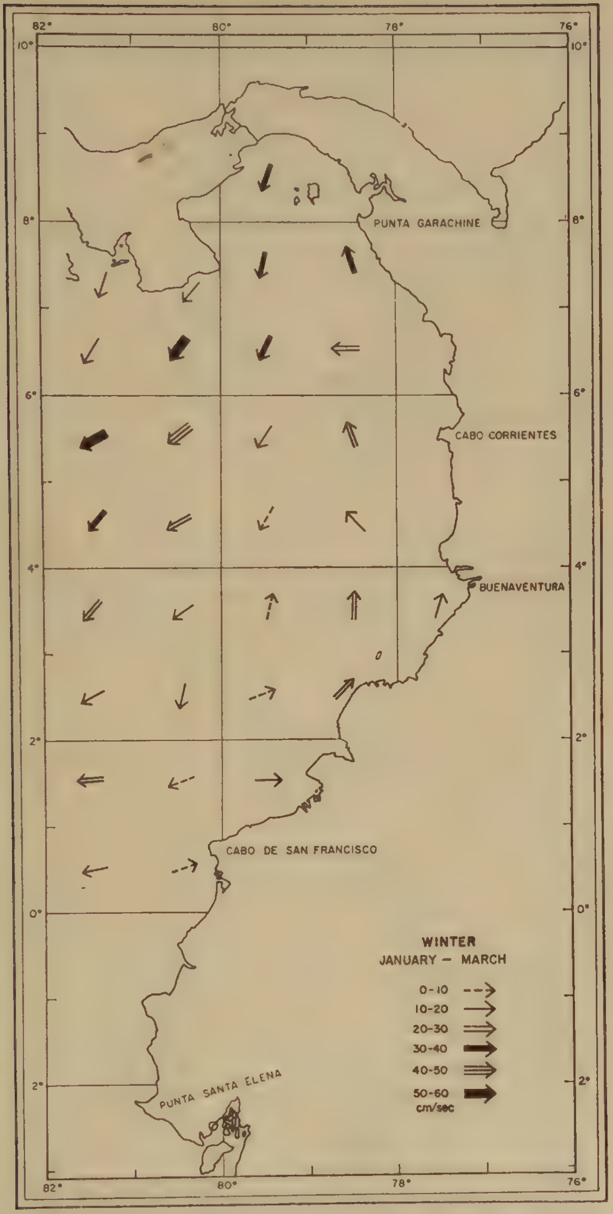
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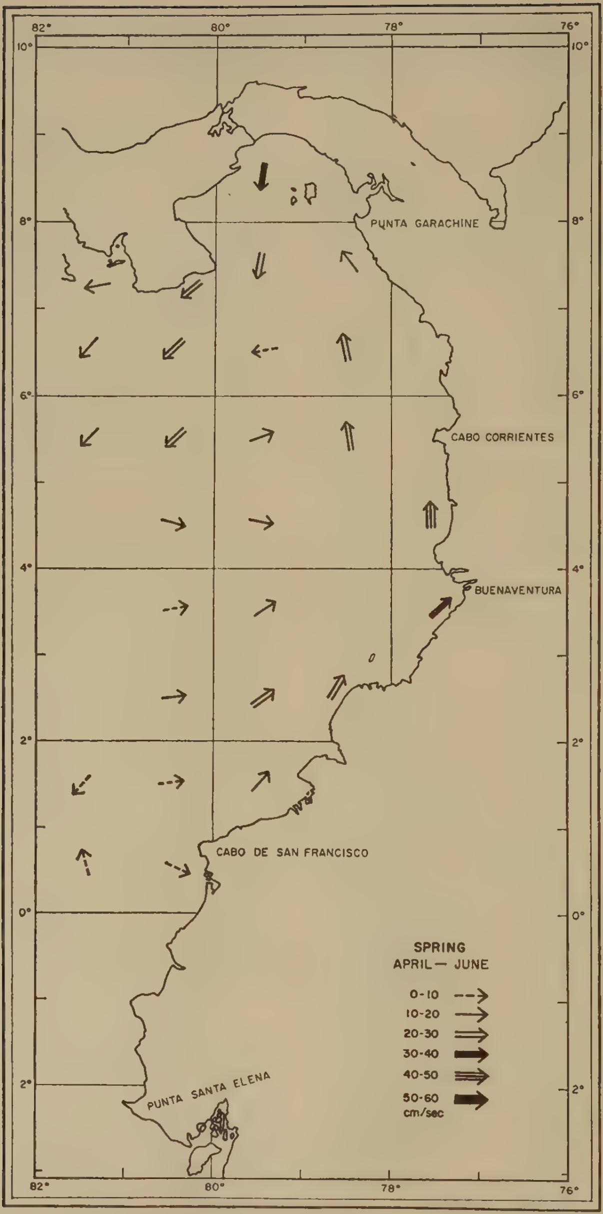
CABO CORRIENTES
BUENAVENTURA
CABO DE SAN FRANCISCO
PUNTA SANTA ELENA
WINTER
JANUARY – MARCH
0-10
10-20
20-30
30-40
40-50
50-60
cm/sec

FIG. 6. Average direction and speed of surface currents by 1-degree squares, after United States Hydrographic Office (1947).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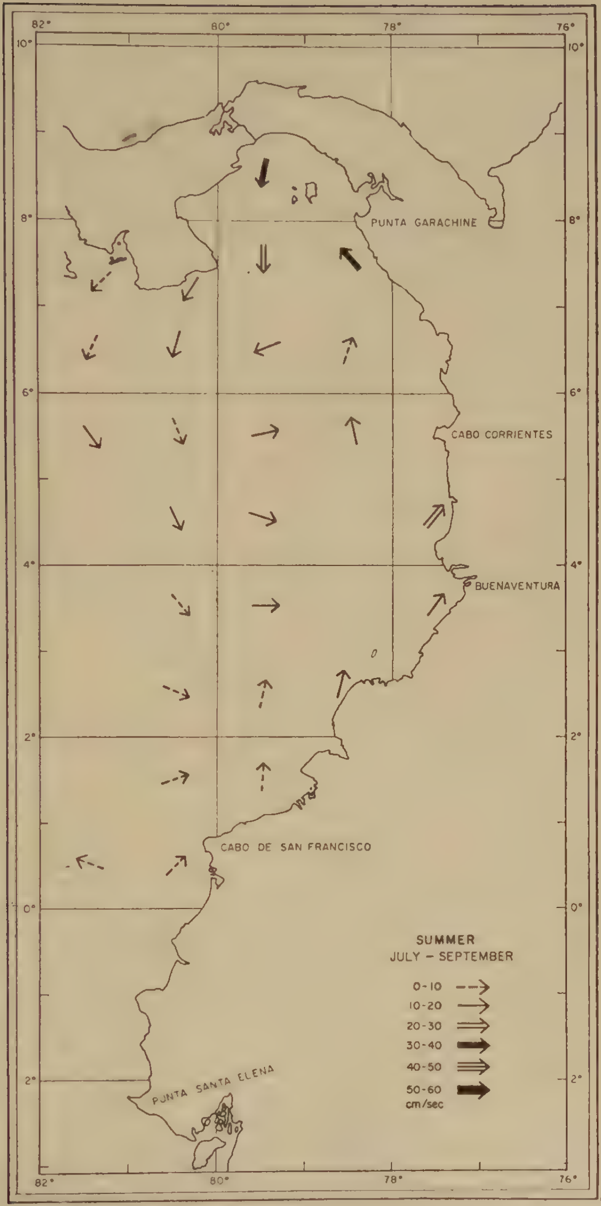
PUNTA SANTA ELENA
SPRING
APRIL — JUNE
0-10
10-20
20-30
30-40
40-50
50-60
cm/sec

FIG. 7. Average direction and speed of surface currents by 1-degree squares, after United States Hydrographic Office (1947).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PUNTA GARACHINE
CABO CORRIENTES
BUENAVENTURA
CABO DE SAN FRANCISCO
PUNTA SANTA ELENA
SUMMER
JULY - SEPTEMBER
0-10
10-20
20-30
30-40
40-50
50-60
cm/sec

FIG. 8. Average direction and speed of surface currents by 1-degree squares, after United States Hydrographic Office (1947).

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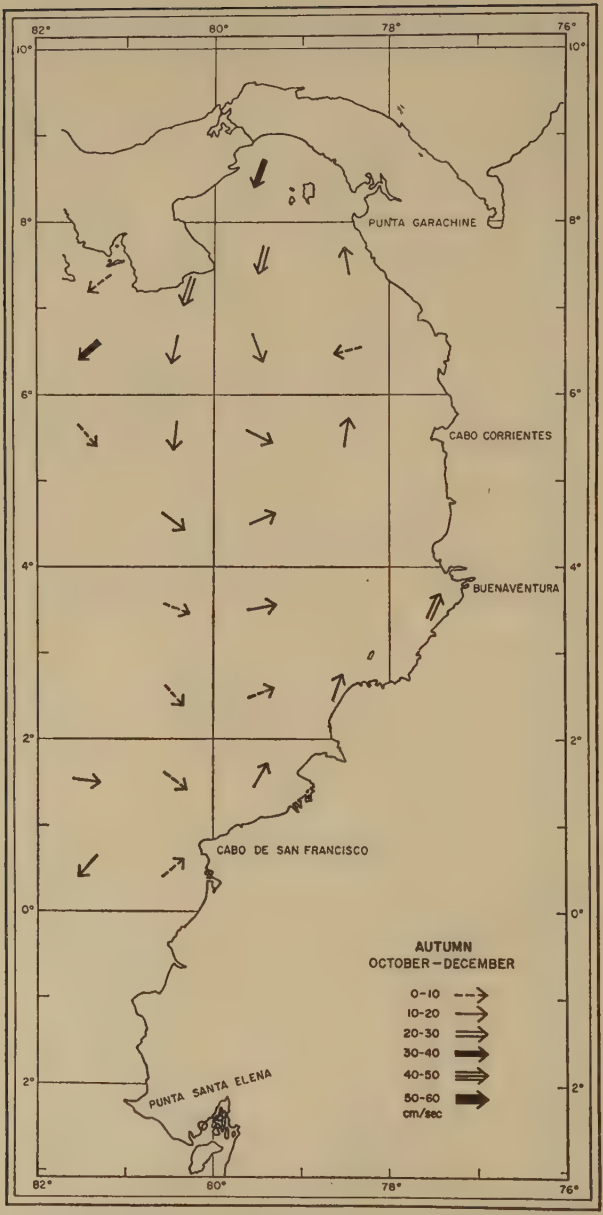
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0°
2°
PUNTA GARACHINE
CABO CORRIENTES
BUENAVENTURA
CABO DE SAN FRANCISCO
PUNTA SANTA ELENA
AUTUMN
OCTOBER – DECEMBER
0-10
10-20
20-30
30-40
40-50
50-60
cm/sec

FIG. 9. Average direction and speed of surface currents by 1-degree squares, after United States Hydrographic Office (1947).

the Pacific. Schott (1935, pls. 31, 32), however, has drawn charts of the average temperature at depths of 200 and 400 meters. These charts show the average temperature in the Panama Bight to be 13° to 14° C. at 200 meters, 9° to 10° C. at 400 meters. No average subsurface salinity or current charts have been prepared for the Pacific.

The characteristic diagram showing the relationship of temperature and salinity provides a useful description of average subsurface conditions. Sverdrup, Johnson, and Fleming (1942, p. 707) show the entire equatorial Pacific to be underlain by an Equatorial Water mass of remarkably uniform character. This Equatorial Water is defined by an envelope enclosing observed points on a temperature-salinity diagram, as shown in figure 10. The water mass as defined lies deeper than 100 meters, because shoaler observations are subject to seasonal variations and local modifications.

In figure 10, temperature-salinity observations have been plotted for 21 stations in the

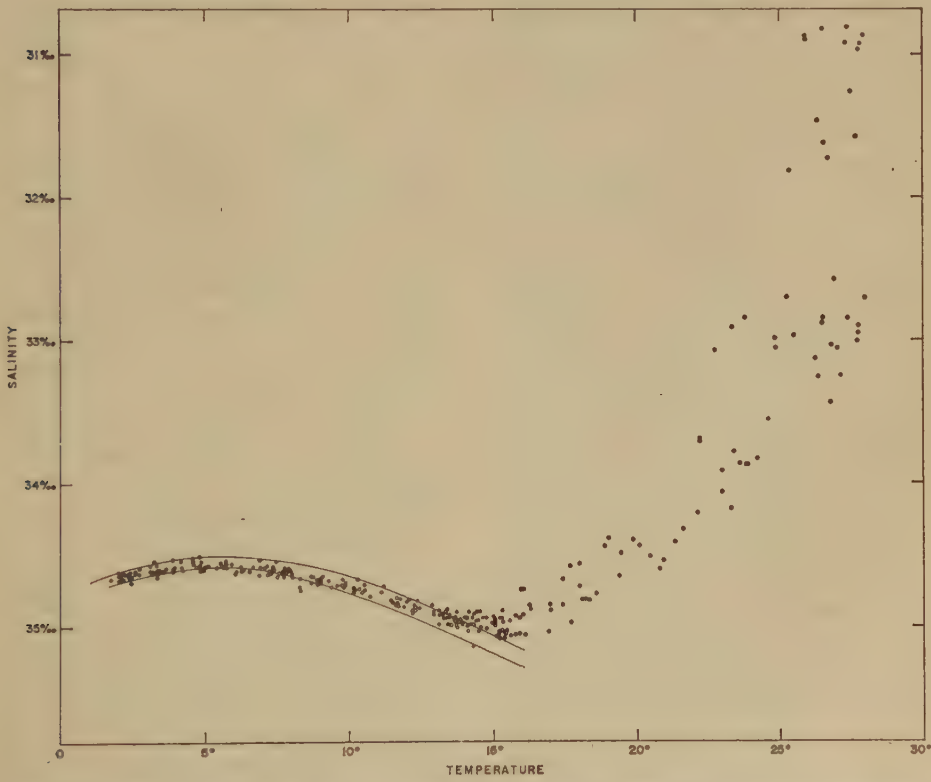

Fig. 10. Temperature-salinity relationship in the Panama Bight. Values at 100 meters and above shown by filled circles. Solid lines show equatorial Pacific water as defined by Sverdrup and others (1942, p. 707). The following stations were used: "Arcturus" 26 (Beebe, 1926); Swedish Deep-Sea Expedition 43, 45 (Bruneau, Jerlov, and Koczy, 1953); "Carnegie" 35, 36, 38, 39, 40 (Fleming and others, 1945); "William Scoresby" 717, 718, 719 (Discovery Committee, 1949); "Dana" 1203, 1205, 1210 (Schmidt, 1929); "Dana" 3548, 3549, 3550 (Carlsberg Foundation, 1937); "Velero" 9 and "Hannibal" 37, 135, 143 (United States Hydrographic Office, 1934).

Panama Bight. These stations include all "Carnegie," "Dana," "Arcturus," and Swedish Deep-Sea Expedition stations in the area, plus representative "William Scoresby," "Valero III," and "Hannibal" stations. All observations from the surface to the greatest depth are plotted, those between the surface and 100 meters being indicated by filled circles. Although the shoal values reflect the lack of uniformity in surface conditions, it is apparent that below 100 meters the waters of the Panama Bight correspond quite closely to the characteristics of Pacific Equatorial Water.

"ASKOY" OBSERVATIONS

TREATMENT OF DATA

"ASKOY" STATION DATA[1] usually consisted of the following observations:

1. DESCRIPTION OF SEA SURFACE CONDITIONS: Wind, sea state, weather, cloud coverage, air temperature, and surface temperature.
2. BATHYTHERMOGRAPH RECORD: In degrees Fahrenheit and fathoms, reaching depths as great as about 70 fathoms (128 meters).
3. TEMPERATURE MEASURED BY REVERSING THERMOMETER: Occasional values at various depths.
4. SALINITY: At various depths on certain stations.

Only a few reversing thermometers were used, and their index corrections are not known. For this reason, when temperature-depth curves were drawn for each station, bathythermograph values were used in preference to reversing thermometer temperatures. Although possibly less accurate, the bathythermograph temperatures appear as a continuous function of depth and thus permit the drawing of a detailed temperature profile.

Salinity values were plotted as functions of temperature on the same station graphs on which the temperature-depth curves appeared. When smooth temperature-salinity curves were drawn, data from nearby stations were used as a guide in interpolation. During this analysis occasional salinity values appeared to be incorrect and were rejected.

Depths of standard isotherms and isohalines were read off from the station graphs and plotted on the temperature and salinity sections. After smooth isotherms were drawn on a temperature section, the appropriate salinity section was placed over it on a light table, and the isohalines were drawn parallel to the isotherms where this did not violate observed values. Thus an attempt was made to eliminate meaningless inconsistencies from the final drawing.

DISTRIBUTION OF SURFACE TEMPERATURE AND SALINITY

The observations of surface temperature and salinity made by the "Askoy" are shown in figures 11 and 12. No attempt has been made to contour these values because of the sparse areal coverage and the non-simultaneity of the observations.

During the southbound trip, surface temperatures of 26° to 28° C. were observed over most of the region, in agreement with Schott's February chart. Only in two areas were temperatures markedly different from Schott's averages: (1) southwest of Malpelo Island surface temperatures exceeded 29° C., about 2° C. higher than average; and (2) in the Gulf of Panama and to the south, surface temperatures were 3° to 4° C. higher than average as far south as latitude 7° N.

During the northbound trip, surface temperatures near the equator were about 3° C. warmer than those shown on Schott's May chart, off Cabo Corrientes about 1° C. warmer, and in the Gulf of Panama about 2° C. warmer than those of Schott.

Comparison of "Askoy" surface salinities (fig. 12) with Schott's February chart shows values distinctly low in the Gulf of Panama and south to latitude 6° N. Where Schott shows surface salinities of 34 to 35 parts per mille, "Askoy" values were less than 34 parts per mille, most observations falling between 32.5 and 33.8 parts per mille. Observations off Punta Santa Elena were in fair agreement with Schott's values, and those in the central part of the Bight were somewhat lower than average. The one station southwest of Malpelo that had both salinity and temperature measurements showed a very low surface salinity (33.13°/₀₀) as well as the high temperature (29.54° C.) noted above. Northbound surface salinities were somewhat lower than the earlier values, but there is no average chart of May salinities with which to compare them.

TEMPERATURE AND SALINITY PROFILES

The subsurface distributions of temperature and salinity are shown in a series of profiles (figs. 13 to 20), the locations of which are shown in figure 1. Certain implications of

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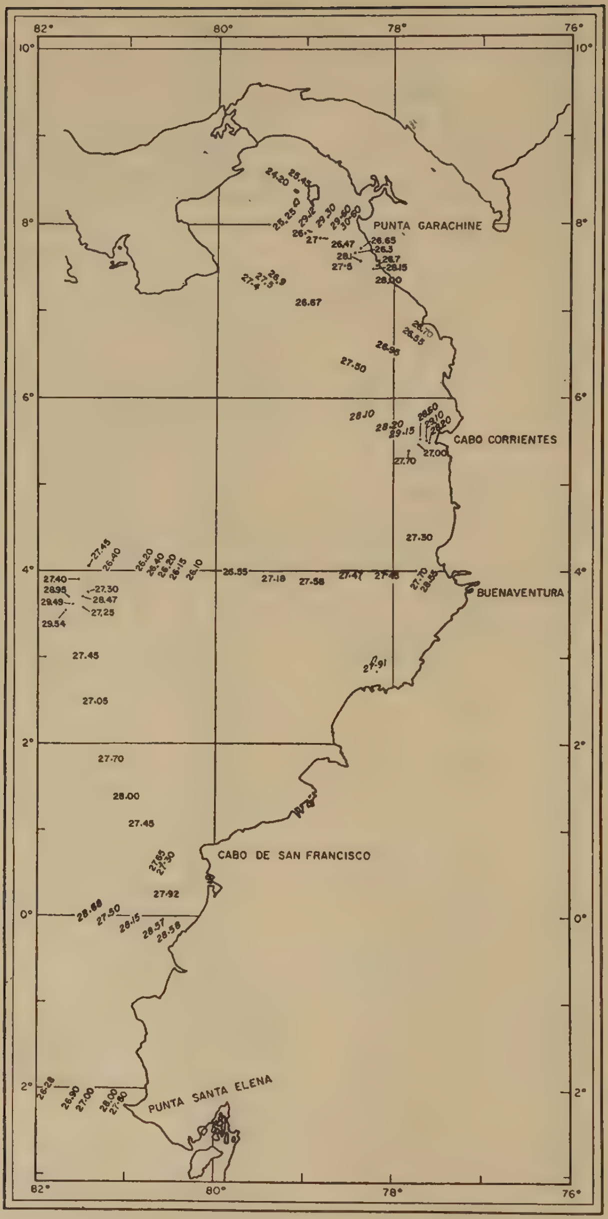
[1] Copies of the station data and bathythermograms are on file at the Scripps Institution of Oceanography.


82°
80°
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10°
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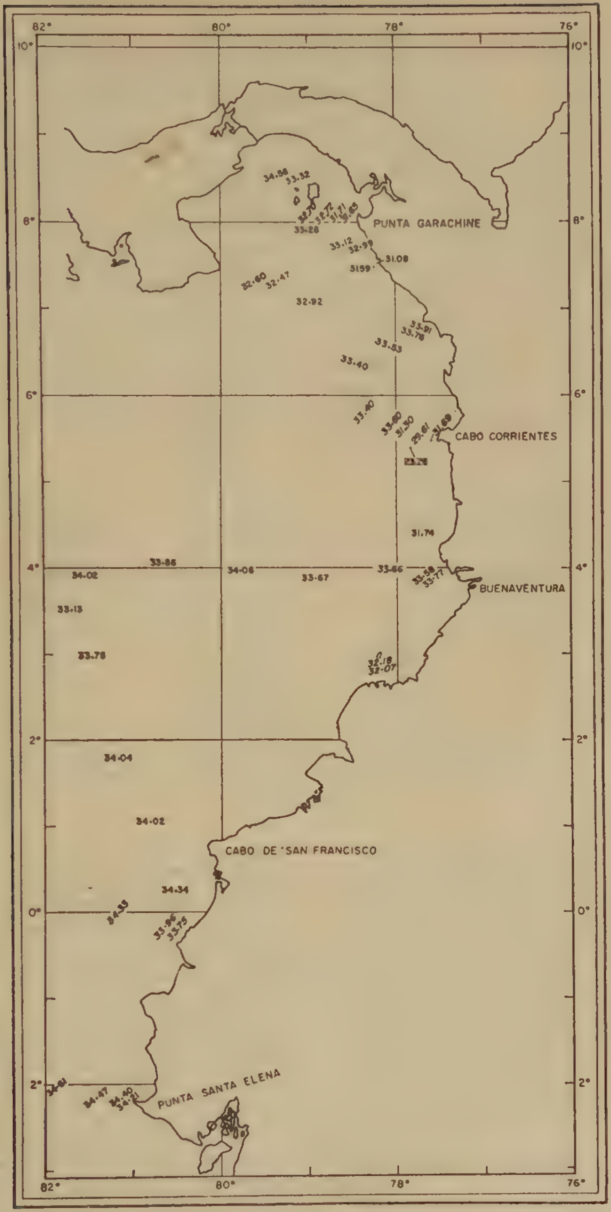
2°
24.20
25.45
25.25
29.12
29.30
29.60
30.60
26.
27.
PUNTA GARACHINE
26.47
26.65
26.3
28.1
26.7
27.5
28.15
28.00
27.4
27.5
26.9
26.67
26.70
26.55
26.95
27.50
28.10
28.20
29.15
28.50
29.10
28.20
CABO CORRIENTES
27.00
27.70
27.30
27.45
26.40
26.20
28.40
26.20
26.15
26.10
26.55
27.18
27.58
27.47
27.48
27.70
28.55
BUENAVENTURA
27.40
28.95
27.30
29.49
28.47
27.25
29.54
27.45
27.91
27.05
27.70
28.00
27.45
27.65
27.30
CABO DE SAN FRANCISCO
27.92
28.66
27.50
28.15
28.57
28.58
26.28
26.90
27.00
28.00
27.80
PUNTA SANTA ELENA

FIG. 11. "Askoy" surface temperature observations, in degrees Centigrade. Upright numerals refer to observations from February 9 to April 12 (southbound); italic numerals, to observations from April 13 to May 23 (northbound).


82°
80°
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8°
6°
4°
2°
0°
PUNTA GARACHINE
CABO CORRIENTES
BUENAVENTURA
CABO DE SAN FRANCISCO
PUNTA SANTA ELENA
34.56
33.32
33.28
33.12
32.99
31.08
31.59
32.60
32.47
32.92
33.91
33.78
33.53
33.40
33.40
33.60
31.50
29.61
31.74
33.86
34.02
34.06
33.67
33.66
33.58
33.77
33.13
33.75
32.18
32.07
34.04
34.02
34.34
33.96
33.75
34.47
34.40
34.21

FIG. 12. "Askoy" surface salinity observations, in parts per mille. Upright numerals refer to observations from February 9 to April 12 (southbound); italic numerals, to observations from April 13 to May 23 (northbound).

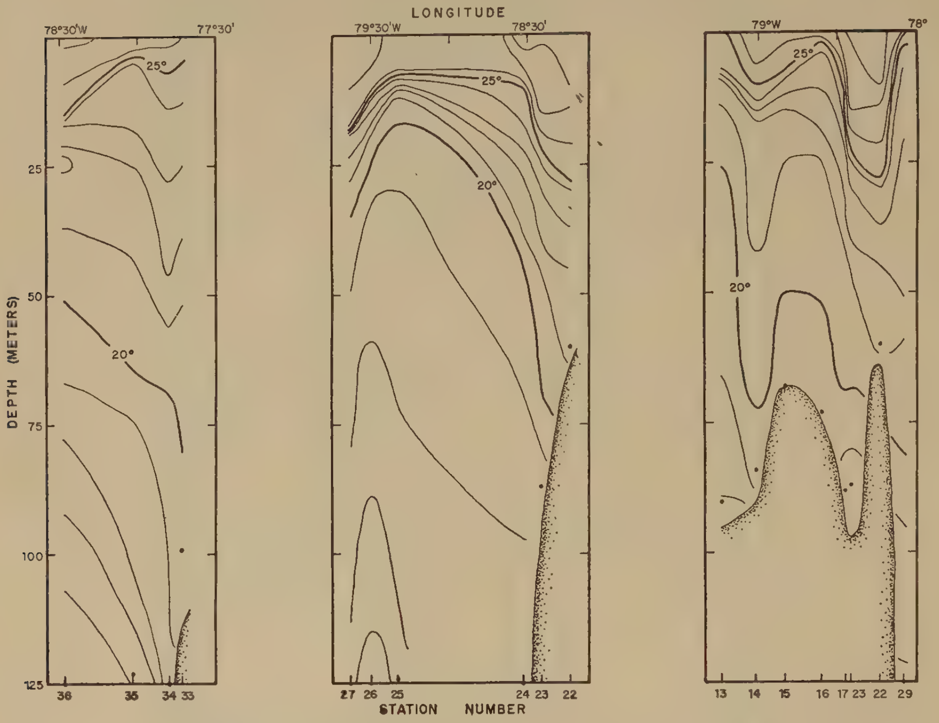

FIG. 13. "Askoy" temperature profiles, in degrees Centigrade, stations 33–36 (March 8–9, 1941, latitude 6° 30′ N.); 22–27 (February 26–27, 1941, latitude 7° 30′ N.); 13–29 (February 22 to March 3, 1941, latitude 8° N.).

the distribution of properties shown in these profiles are discussed below, but here only a general description is attempted.

The relatively high surface temperatures (26° to 29° C.) discussed above are characteristic of only a rather thin surface layer. This surface homogeneous layer is nowhere deeper than 25 meters, a relatively shallow thermocline being found over the entire area. At a depth of 100 meters temperatures range from 15.8° to 19.5° C., 84 per cent of the observations falling between 16.0° and 18.0° C. In the northern part of the Panama Bight isotherms show a general downward trend as they approach the coast (stations 13 to 22, 25 to 22, and 36 to 33, fig. 13; stations 99 to 94, fig. 19). South of Cabo Corrientes this does not seem to be the case (figs. 15 and 19), except possibly very close inshore on the profile west of Buenaventura (fig. 15).

The relatively low surface salinities (less than 34°/₀₀) are also found only in the surface layer, a halocline occurring at about the same depth as the thermocline. At a depth of 100 meters the range of salinity is very small (34.87 to 35.05°/₀₀), 59 per cent of the observations falling between 35.00 and 35.05 parts per mille. The isopleths of salinity also show a downward trend towards the coast north of Cabo Corrientes (fig. 14). However, neither the profile west of Corrientes (stations 99 to 94, fig. 20) nor the profiles farther south (figs. 16 and 20) show this feature.

On the two long profiles (figs. 15 to 18), on the other hand, both the isotherms and the isopleths of salinity offshore trend downward towards the vicinity of Malpelo Island. This trend and those discussed above are consistent with the general counterclockwise surface circulation inferred for the area.

Effects of Heavy Precipitation and Runoff

The relatively low coastal salinities (less than $33^{\circ}/_{\circ\circ}$) off Buenaventura shown in Schott's February chart (fig. 4) and the characteristically low salinities (from $33^{\circ}/_{\circ\circ}$ to less than $28^{\circ}/_{\circ\circ}$) throughout the Panama Bight shown in Schott's August chart (fig. 5) are undoubtedly influenced by heavy precipitation and runoff. During August average surface salinities increase steadily with distance from the coast, and the mean surface salinity of the Equatorial Countercurrent, probably the chief advective source of surface water to the region, is in excess of 33 parts per mille.

An attempt was made to estimate the effect of rainfall and runoff on coastal surface salinities, although such an estimate must be crude because of the approximations involved in the computation. The assumptions involved in this estimate are as follows:

1. The average annual river discharge from the Pacific watershed of Colombia is 8000 cubic meters per second (Manuel, 1955, pp. 40–41).
2. The total annual precipitation in the area is 300 cm., and the seasonal precipitation and evaporation can be estimated by the methods of Jacobs (1951).

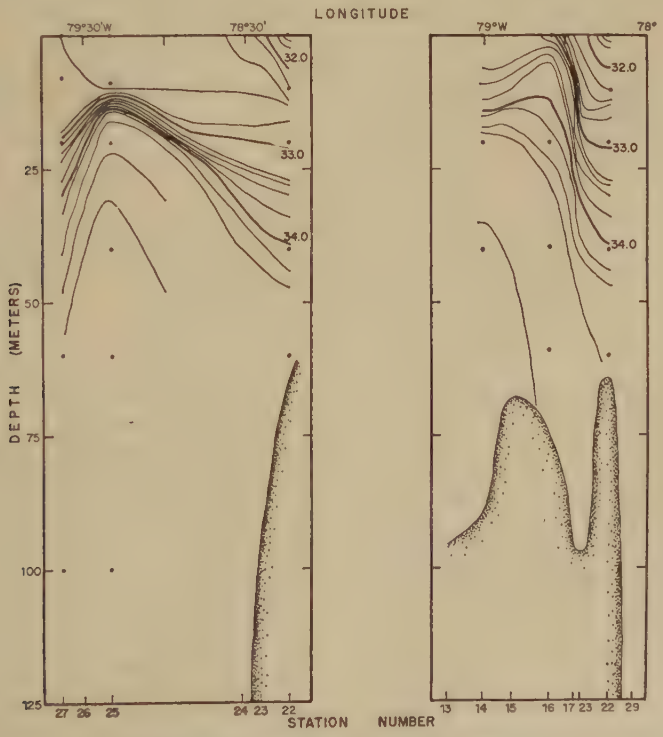

FIG. 14. "Askoy" salinity profiles, in parts per mille, stations 33–36 (March 8–9, 1941, latitude 6° 30′ N.); 22–27 (February 26–27, 1941, latitude 7° 30′ N.); 13–29 (February 22 to March 3, 1941, latitude 8° N.).

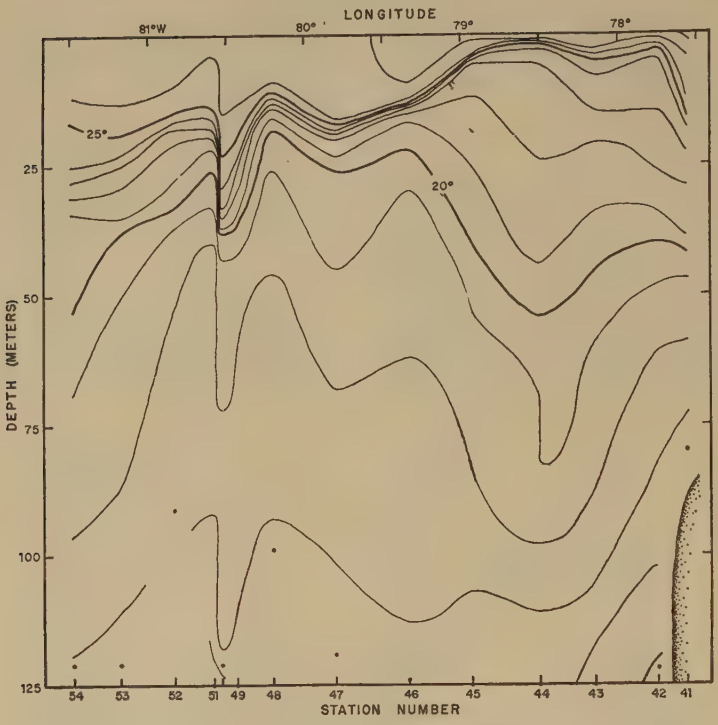

FIG. 15. "Askoy" temperature profile, in degrees Centigrade, stations 41–54 (March 20–25, 1941, latitude 4° N.).

3. Fresh water added to the surface layer of the region being examined is neither carried out of the region nor mixed with deeper waters.

The results of this calculation show that during the period June to August the salinity of a 10-meter layer of water 300 miles long by 60 miles wide could be reduced by rainfall and runoff from 33 parts per mille to 28 parts per mille in 78 days. During the rainiest period, September to November, only 65 days would be required, while during the period December to May 172 days are necessary.

UPWELLING IN THE GULF OF PANAMA

As mentioned above, during the months of January through March the effect of the prevailing northerlies is to drive surface water out of the Gulf of Panama, leading to replacement and mixing with deeper water. The seasonal march of surface conditions shows the lowest temperatures and highest salinities during February and March, and the average sea level, which is in large part a function of the specific volume of the water, is also lowest during the same period (see Fleming, 1940, fig. 6; and Schaefer, Bishop, and Howard, 1958, figs. 1, 3).

Although this "spring" upwelling is a consistent annual phenomenon, its intensity appears to vary considerably from year to year. This is clearly shown in figure 21, based on records of the Panama Canal Company. It is obvious, for example, that the average February-March sea level was higher in 1941 than in all other years of the record, and that the average February-March surface temperature was higher, and the number of cold days fewer, than in all other years, with the exception of 1928. Conditions in 1933, in contrast, seem to have been much closer to average (as shown by the 42-year mean).

A comparison of profiles made in March, 1933, by the U.S.S. "Hannibal" (United States Hydrographic Office, 1934) with those of the "Askoy" in late February, 1941, shows the striking difference between these two years (fig. 22 shows the locations and dates of the compared profiles).

In February, 1941 (fig. 13), a thin layer of warm water (warmer than 26° C.) covered the surface, a strong thermocline centered on the isotherm of 23° C. was located at depths of 10 to 40 meters, and waters between 50 and 100 meters had a temperature of 17° to 21° C. Surface salinities (fig. 14) were low (31.6 to 33.4°/₀₀) above a strong, shallow halocline, and waters between 50 and 100 meters had a salinity of 34.5 to 34.8 parts per mille. In March, 1933 (fig. 23), on the other hand, surface temperatures were usually less than 20° C., a weaker thermocline centered on the isotherm of 17° C. lay at a depth of less than 20 meters, and waters between 50 and 100 meters had a temperature of less than 15° C. Surface salinities (fig. 24) were high (34.6 to 34.8°/₀₀), there was no pronounced halocline, and waters between 50 and 100 meters had a salinity of 34.8 to more than 35.0 parts per mille.

Thus it seems likely that, whereas upwelling was well developed in 1933, it was weak or missing in 1941. One might expect the explanation of this difference between the two years to lie in a difference in the strength of the northerly winds, as Schaefer and his coauthors have demonstrated the significant

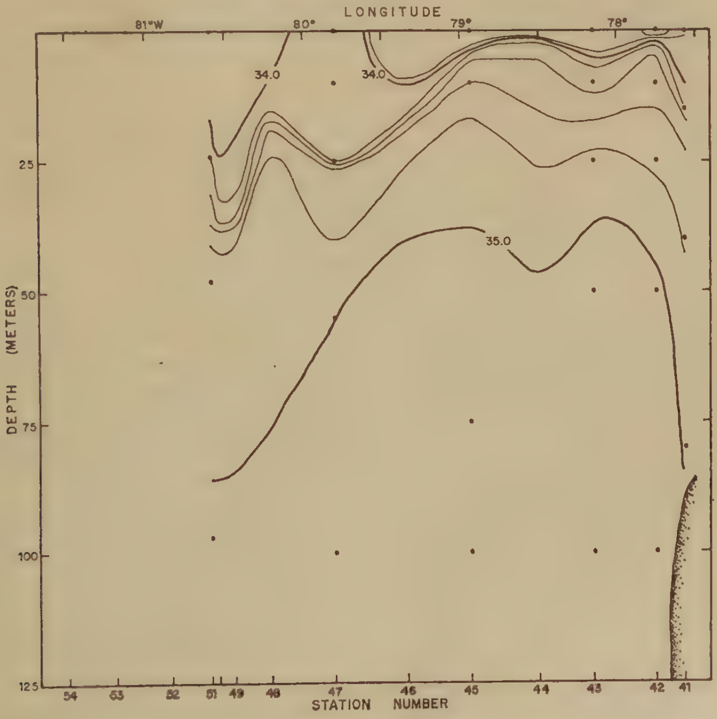

FIG. 16. "Askoy" salinity profile, in parts per mille, stations 41–54 (March 20–25, 1941, latitude 4° N.).

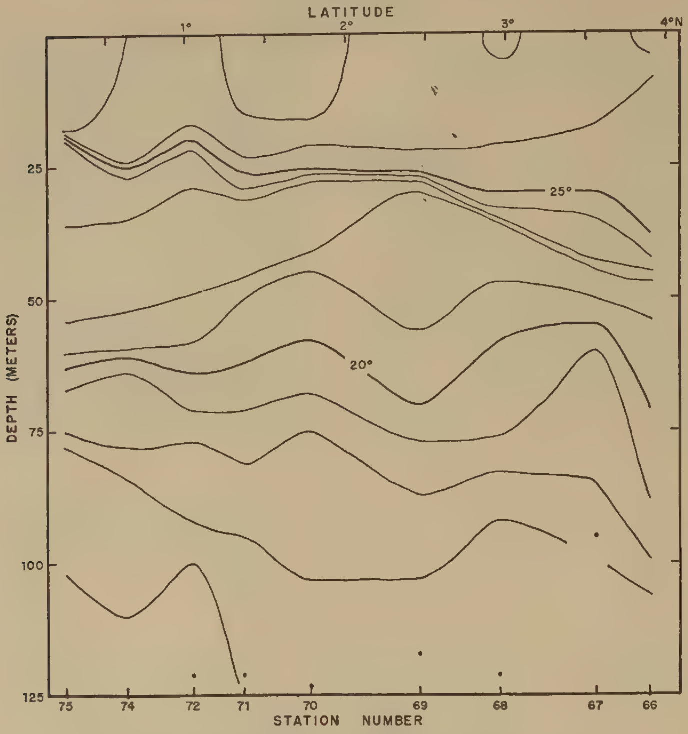

FIG. 17. "Askoy" temperature profile, in degrees Centigrade, stations 66–75 (March 29 to April 2, 1941, longitude 81° W.).

correlation between the spring (January through April) values of all northerly winds (total miles of winds from north, northwest, and northeast) and mean spring sea levels at Balboa.

In an attempt to refine their analysis, an index of northerly wind stress was computed for the February-March period of each year. This period was selected as the time when mean sea levels and sea surface temperatures are usually lowest, that is, the period when upwelling is best developed. The wind-stress index was computed by adding the total miles of wind from true north for February and March to the northerly component of the total miles of northwesterly winds for the same period (northeasterly winds at Balboa are negligible). This sum, divided by the number of hours in the two-month period, gave an average northerly component of the wind velocity in miles per hour, the square of which is the wind-stress index.[1]

The lowest panel of figure 21 shows the year-to-year variations of this index. Correlation of the index with the average February-March sea level gave the significant correlarion coefficient, r, of -0.54. As the figure shows, the wind-stress index was smaller (46.5) in 1941 than in 1933 (63.4), the 42-year average being 65.9. However, the difference is clearly not sufficient to account for the marked departure from mean sea level observed in 1941.

Thus the full explanation must lie elsewhere. Schaefer and his co-authors investigated the multiple correlation between Balboa sea surface temperature, Balboa northerly winds, and offshore temperatures in a 5-degree square at approximately latitudes 5° to 10° N., longitudes 80° to 85° W. (from records of the Japanese Imperial Marine Observatory at Kobe for the years 1916 to 1938), and concluded that Balboa spring temperature anomalies were affected partly by local effects of northerly winds, and partly by factors affecting the temperatures over a large area (as measured by the offshore temperatures).

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[1] The force of friction of the wind on the sea surface, the wind stress, is proportional to the square of the speed of the wind relative to the water.

Unfortunately, because of the lack of published offshore data after 1938, it is not easy to investigate the possibility that the unusually high sea level in the Gulf of Panama in 1941 was associated not only with a reduction in the northerly wind stress but also with some other large-scale process affecting the temperature over a large area. There is some evidence from the "Askoy" observations that this was the case (see below), and the fact that both in 1941 and 1953 (another year with unusually high sea level) *El Niño* was observed in Peru makes this possibility particularly intriguing.

El Niño IN 1941

One of the most celebrated of oceanic disturbances is that known as *El Niño*, which is occasionally reported from the coast of Peru. There is fairly convincing evidence that this phenomenon occurred during the early months of 1941 (see Schweigger, 1942; Sears, 1954; Lobell, 1942; Fiedler, Jarvis, and Lobell, 1943; Vogt, 1942). Because it is likely

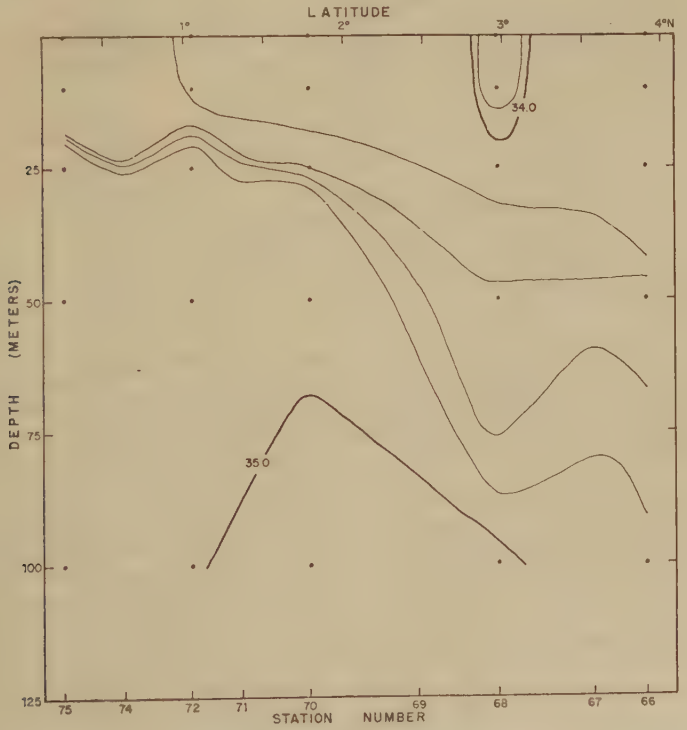

FIG. 18. "Askoy" salinity profile, in parts per mille, stations 66–75 (March 29 to April 2, 1941, longitude 81° W.).

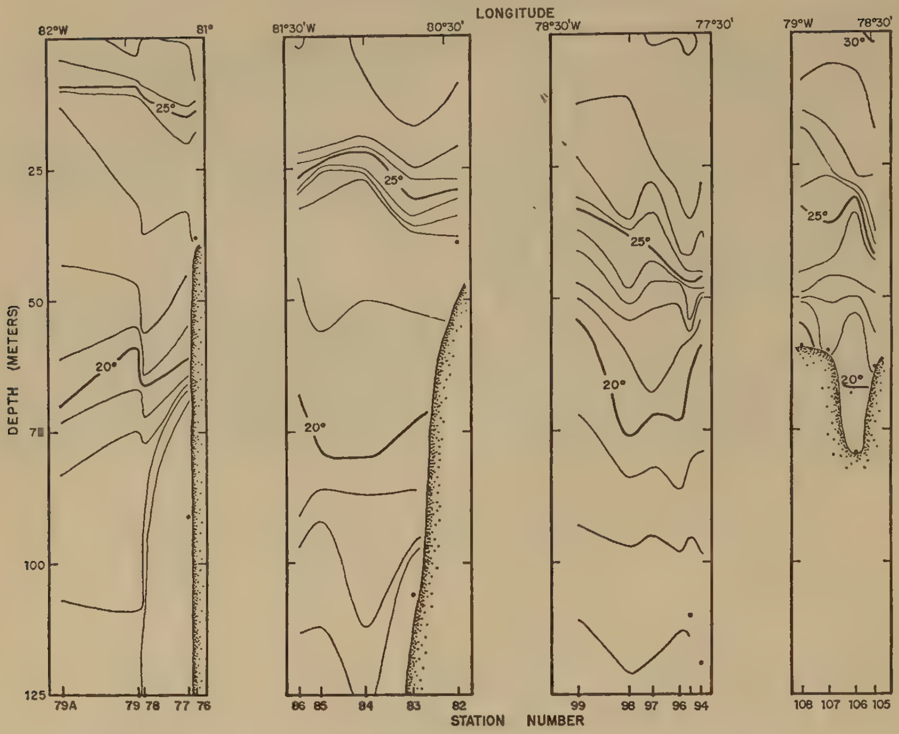

FIG. 19. "Askoy" temperature profiles, in degrees Centigrade, stations 76–79A (April 10–11, 1941, latitude 2° S.); 82–86 (April 15–16, 1941, 0°); 94–99 (May 13, 1941, latitude 5° 30′ N.); 105–108 (May 22–23, 1941, latitude 8° N.).

that *El Niño* is not merely a local Peruvian condition, but rather reflects a large-scale change in atmospheric conditions, it is of interest to compare the "Askoy" observations with those to be expected during such an event.

The generally accepted description of *El Niño* is that of Schott (1931). According to him, the Intertropical Convergence, which usually lies across the coast near the Ecuador-Colombia border during the early months of the year, occasionally and for unknown reasons penetrates southward several hundred miles to northern Peru. The southeast trades of that region are replaced by calms or northerlies, bringing heavy rains to this otherwise desert area. At the same time warm, low-saline waters flow southward from the Equatorial Countercurrent, covering or replacing the usual cold and high-saline waters of the Peru Current southward nearly to latitude 15° S.

The southward displacement of the Intertropical Convergence has other effects farther north. A tongue of cold water extends southwestward from the Gulf of Panama nearly to the equator, with temperatures less than 25° C. and salinity higher than 34 parts per mille. These characteristics of low temperature and high salinity are attributed to the arrival of subsurface waters at the surface, presumably owing to the action of northerly winds in removing surface waters of the Gulf. On the basis of observations made by the "Königsberg" in March, 1931, Schott seems to accept the fact that such characteristics may always be present in and south of the Gulf of Panama during the first months of the year, although he leaves the impression that they are more exaggerated during a year of *El Niño*.

Farther offshore the Equatorial Countercurrent lies south of its usual position, eastward currents having been reported from the Galápagos. During the 1891 event the "Albatross" also reported heavy rains and lush vegetation in the Galápagos during March. Schott considers that the warm, low-saline waters west of the Panama cold tongue and in the countercurrent are the source of *El Niño* "current."

Because none of the "Askoy" observations were made off the coast of Peru, they cannot be used to test the validity of Schott's model in that region; nor do they help in our determining the westward extent of the phenomenon of *El Niño*. They do, however, fall exactly in that region where, according to Schott's description, should be found the cold tongue extending southward from the Gulf of Panama.

Examination of the "Askoy" data does not reveal such a tongue. Surface temperatures lower than 25° C. were observed on only one station, and temperatures in the Gulf and south were several degrees higher than usual. Salinities higher than 34 parts per mille were consistently observed only south of about latitude 2° S., and north of there most values fell between 32.5 and 33.8 parts per mille, or somewhat lower than usual.

The data from the Gulf of Panama suggest

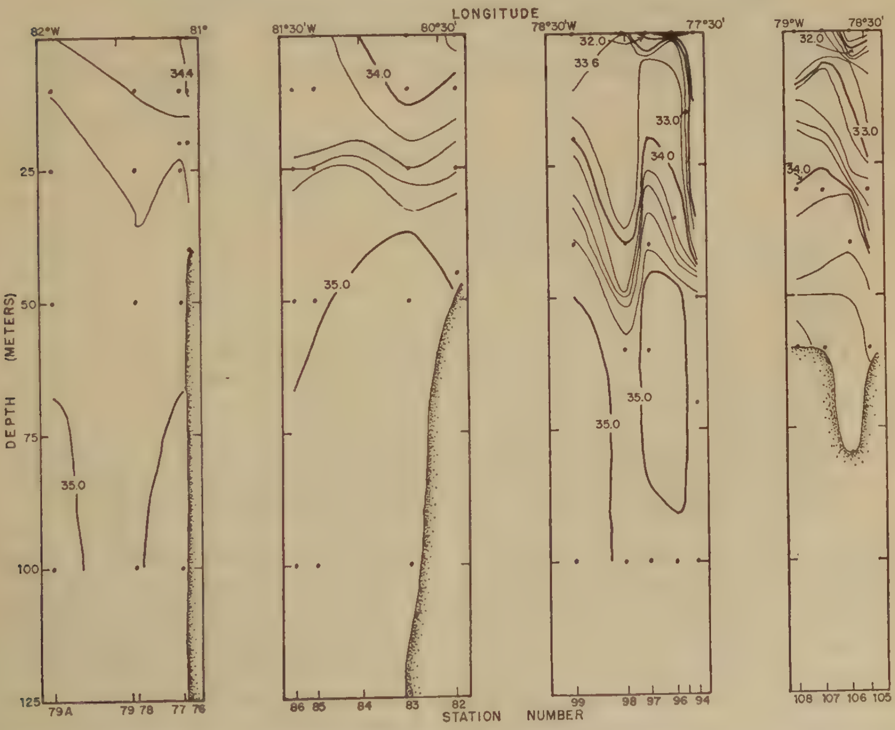

Fig. 20. "Askoy" salinity profiles, in parts per mille, stations 76-79A (April 10–11, 1941, latitude 2° S.); 82–86 (April 15–16, 1941, 0°); 94–99 (May 13, 1941, latitude 5° 30′ N.); 105–108 (May 22–23, 1941, latitude 8° N.).

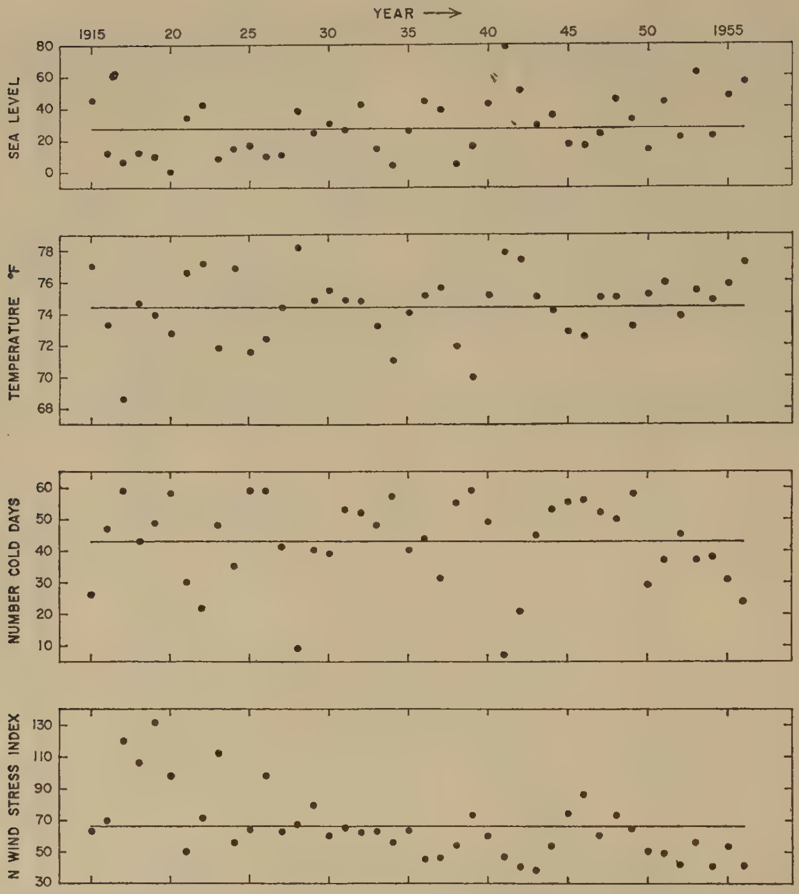

FIG. 21. Year to year variations in February–March values at Balboa of average sea level (hundreds of feet), average sea surface temperature (in degrees Fahrenheit), number of cold days (when sea surface temperature fell below 76° F.), and northerly wind-stress index (see text). In each case, horizontal line shows 1915–1956 mean.

that, far from being a year of unusually intense upwelling in the Gulf, 1941 was a year of much reduced upwelling. As discussed above, waters in the Gulf were much warmer and less saline in 1941 than in 1933, and the pronounced shallow thermocline at the time of the "Askoy" observations is further evidence that upwelling was not active. In 1925, on the other hand, both sea level and sea temperatures were lower than usual. Thus *El Niño* of 1941, at least as shown by conditions in the Gulf of Panama, was significantly different from that of 1925 as described by Schott.

In the region northwest of the cold tongue, Schott found the highest surface temperatures (higher than 28° C.) and low salinities (less than 32°/₀₀ to less than 33°/₀₀), and this water, coming from the Equatorial Countercurrent, he considered as the source of *El Niño* waters. During the 1953 *Niño* (Posner, 1957), a center of warm water (higher than 28° C.) and low salinity (31–32°/₀₀) was observed south of Costa Rica. Wooster and Jennings (1955), who described this situation, suggested that southward movement of this water contributed to the unusual conditions observed between Ecuador and the Galápagos.

It seems likely that similar conditions were observed by the "Askoy" west of Malpelo Island. It will be recalled that surface temperatures of greater than 29° C. and surface salinities as low as 33.1 parts per mille were recorded on station 58 southwest of Malpelo. Data from this and a neighboring station (66) show that the warm, fresh water was confined to a surface layer only about 20 meters thick.

Murphy, in his unpublished journal, comments on this layer of warm water and on the great change of horizontal velocity at about 20 meters, as evidenced by the pronounced wire angle developed when instruments reached that depth. He estimated that this surface layer was moving southward at a speed in excess of 1.5 knots, and speculated: "This warm water may represent one of the major transgressions of northern hemisphere water across the equator. It may be an early stage of a *Niño* phenomenon in Peru, or it may even be synchronous with one. In the latter case the inference would be that the warm Pacific water moves more or less eastward toward the land all along the northerly half of the South American coast."

OBSERVATION OF AN OCEANIC FRONT

In a recent paper Cromwell and Reid (1956) described a phenomenon which they call an "oceanic front." The front is defined as a band along the sea surface across which there is an abrupt change of density. The front is often visible as a narrow band of agi-

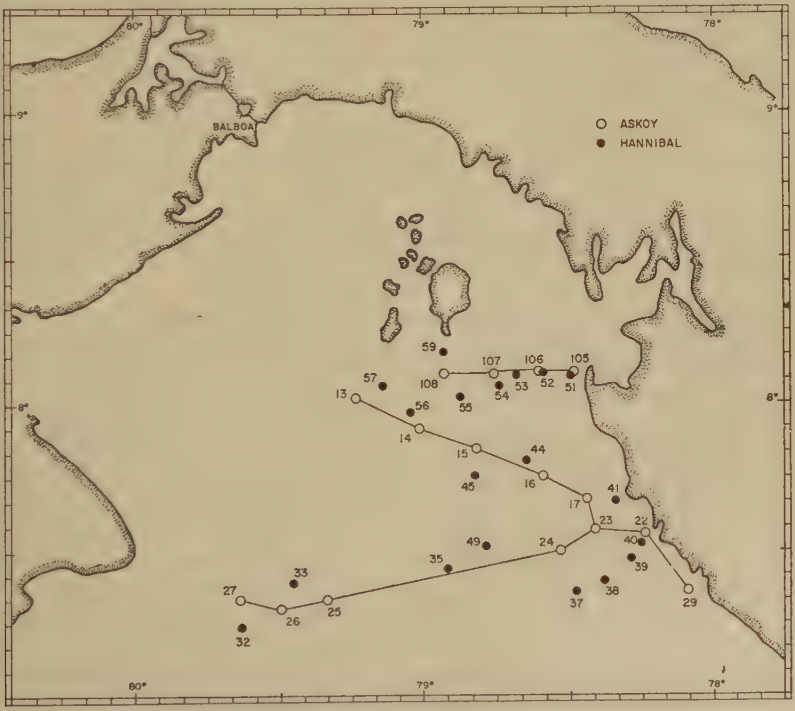

FIG. 22. Location of "Hannibal" stations used in the preparation of figures 23 and 24.

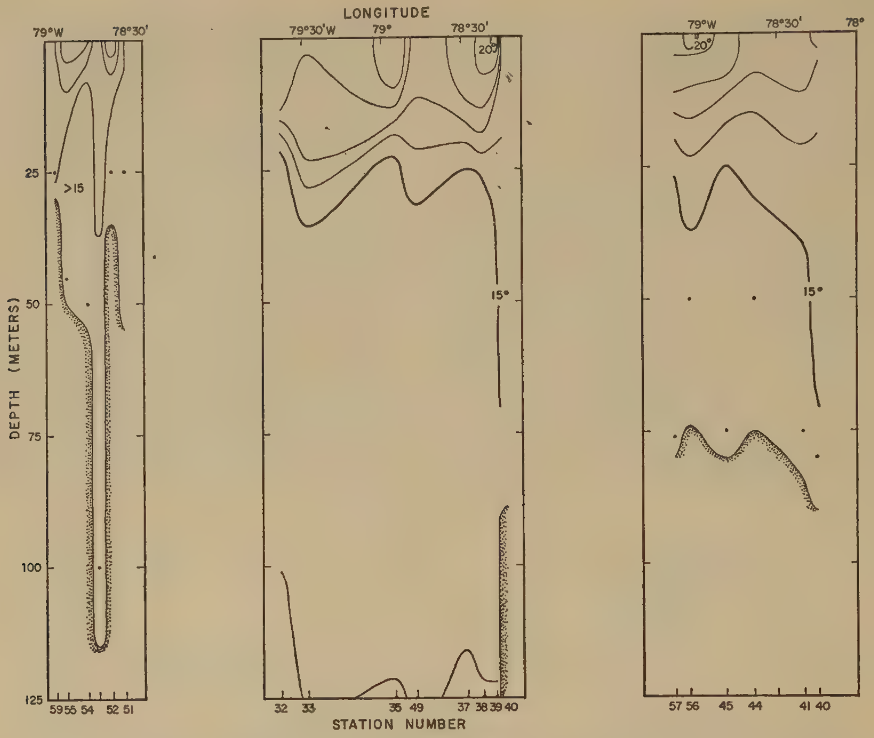

FIG. 23. "Hannibal" temperature profiles, in degrees Centigrade, stations 51–59 (March 15–16, 1933, latitude 8° N.); 32–40 (March 10–12, 1933, latitude 7° 30′ N.); 40–57 (March 12–15, 1933, latitude 8° N.).

tated wavelets following a sinuous path, and often floating debris is concentrated along this band. Frequently there is also a distinctive sound, apparently produced by the breaking wavelets.

The unusual distribution of isotherms between stations 49 and 51 on the profile west of Buenaventura (fig. 15) is very reminiscent of the subsurface distribution at a front (see Cromwell and Reid, 1956, fig. 3), although on the "Askoy" stations no abrupt change in surface temperature was observed. Below the surface, however, there was a pronounced discontinuity in temperature from east to west. East of the feature there was a warm isothermal layer lying above a strong thermocline, and also apparently there occurred the deep penetration of warm water as described by Cromwell and Reid. West of the feature the vertical temperature gradient in the thermocline is much smaller and the warm surface layer somewhat shallower.

The surface manifestations of this phenomenon near station 49 have been vividly described by Murphy (*in* Nichols and Murphy, 1944). He writes of areas of "dancing water" and of the sound produced by this motion, with glassy calm on one side of the front and turbulent water on the other. In the vicinity of the front were concentrated great numbers of organisms, ranging in size from blackfish (*Globicephalus*) to minute plankters.

There are not enough closely spaced bathythermograph observations to permit detailed comparison with the oceanic fronts described by Cromwell and Reid. According to the surface temperature data (26.15° C. on station 49, 26.20° C. on station 50, 26.40° C. on station 51), this was not a front as these authors define one, because there was apparently no abrupt change in surface density. Yet the other surface manifestations and the subsurface distribution of temperature seem to correspond very closely with the phenomenon they describe.

The Colombia Current

The surface current charts discussed above (figs. 6 to 9) show throughout the year a northward-flowing surface current along the coast of South America north of Cabo de San Francisco. This current is apparently well known, being described in the "Sailing directions for South America" (United States Hydrographic Office, 1952, p. 21) as follows: "1.82 Ecuador and Colombia—The Peruvian Current divides at Parinas Point, one branch setting to the westward and the other along this coast and into the Bay of Panama. Off the coast of Ecuador this current is constant within 60 miles of the land, and is of great assistance to vessels bound to Panama."

Murphy (1939) has indicated the unlikelihood of the coastal current's being derived from the Peru (Humboldt) Current. Because of the permanence of this current, and because (as discussed below) it does not seem to be a branch of the Peru Current, I propose that this current be called the "Colombia Current." The average current charts suggest that it has a mean speed of about 25 cm. per

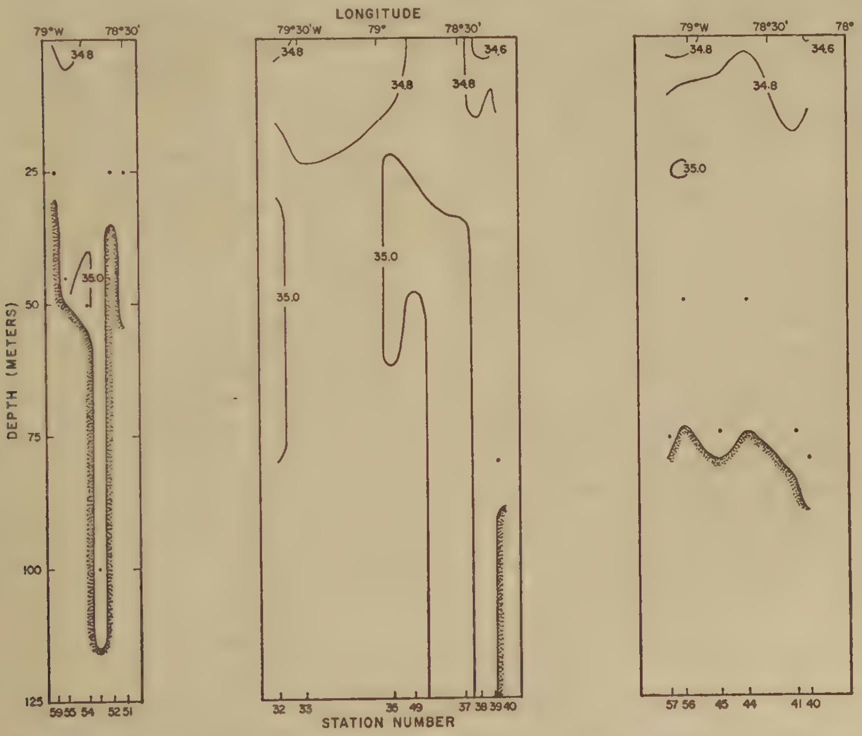

Fig. 24. "Hannibal" salinity profiles, in parts per mille, stations 51–59 (March 15–16, 1933, latitude 8° N.); 32–40 (March 10–12, 1933, latitude 7° 30′ N.); 40–57 (March 12–15, 1933, latitude 8° N.).

second (0.5 knot) and a width of less than 100 miles.

The prevailing winds along the coast of Colombia blow from the south parallel to the coast during most of the year, blowing from the north only during the winter. Within a few degrees of the equator, where there is very little deflecting force due to the rotation of the earth, one would expect transport of the surface wind-driven current to be in the direction of the wind; farther north, transport would be to the right of the wind. Thus, during the seasons when the modified southeast trades prevail, one would expect a northward current along the coast converging with the coast and having a thermocline deeper inshore than offshore (thus with the sea surface sloping downward away from the coast). As mentioned above, this appears to be the case north of Cabo Corrientes and possibly close inshore off Buenaventura. On these profiles lowest surface salinities are also found close inshore, contributing to the shoreward increase in height of the sea surface. As the "Askoy" data are so shallow, and so many of the observations are close to the equator, it seems futile to attempt a calculation of velocity or transport of this current.

Neither the circulation suggested above nor the distribution of properties observed is consistent with the existence of coastal upwelling. Offshore, however, the thermocline is very shallow (less than 10 meters on stations 42 to 45), in part because of the equilibrium distribution of mass resulting from the wind-driven circulation. Such a shallow thermocline (designated a "dome" by Cromwell, 1958) may be associated with high productivity both because of the ready availability of waters of high nutrient content in the thermocline to the stirring action of the wind, and because the euphotic zone may extend downward into the thermocline where nutrients can be supplied by lateral mixing.

Direct measurements of the surface current were attempted during the "Askoy" expedition with a Coast and Geodetic Survey log line and pelorus. On station 91, inshore of Gorgonilla Island, where 34 observations were made between 1335 on April 25 and 1600 on April 26, 1941, the surface current was usually towards the east (044° to 095° magnetic) parallel to the coast, with a mean speed of about 25 cm. per second (during the first hour and a half the current was stronger than 50 cm. per sec.; later it varied from 10 to 45 cm. per sec.). On station 92, less than a mile west of Cabo Corrientes, nine observations were made between 1145 and 1635 on May 12, 1941. Here the direction varied from northward to southward, the speeds from 5 to 30 cm. per second. Because these stations were so near shore, the measurements tell little about the mean drift of the Colombia Current.

It is conceivable that the waters of the Colombia Current are derived from the Peru Current. If so, they are extensively modified by mixing, local heating, and freshening due to rainfall and runoff. Although one might look for the presence of Peru Current indicator species, it seems unlikely that many of the indigenous plankton organisms of the Peru Current will be found in the Colombia Current, because near-surface conditions are drastically different. Crossings of the north boundary of the Peru Current show an abrupt change in the distribution of temperature and dissolved substances (Wooster and Cromwell, 1958), and it is probable that most of the waters of the Peru Current turn westward south of the equator. At our present state of knowledge, the Colombia Current must be considered merely the eastern limb of the general counterclockwise circulation of the Panama Bight.

SUMMARY

THE PANAMA BIGHT may be defined as that part of the eastern tropical Pacific Ocean that lies between the Isthmus of Panama (about latitude 9° N.) and Punta Santa Elena (about latitude 2° S.) and extends westward from the coasts of Panama, Colombia, and Ecuador to about longitude 81° W. Oceanographic observations discussed in this region were made by the "Askoy" expedition during the period February 9 to May 26, 1941.

Bathymetrically the region is part of the Panama Basin which is enclosed by Central and South America, Cocos Ridge, the Galápagos Islands, and Carnegie Ridge. Most of the Panama Bight is deeper than 3000 meters, the shelf being nowhere wider than 30 miles except in the Gulf of Panama which is less than 200 meters deep.

Seasonal contrasts in weather within the Bight are related to movement of the Intertropical Convergence. In January–March the Intertropical Convergence is farthest south, offshore northerlies cause upwelling in the Gulf of Panama, and the Gulf experiences its dry season. In July–September the Intertropical Convergence is farthest north, and the region south of Cabo de San Francisco receives its least rain. The central part of the Bight receives heavy rainfall throughout the year. From June to November most of the Panama Bight is dominated by southwest winds.

These seasonal changes are reflected in the average surface distribution of temperature and salinity. In February surface temperatures of 26° to 28° C. and salinities of 34 to 35 parts per mille are found in most parts of the Bight, with lower temperatures in the Gulf of Panama. By August low surface temperatures have disappeared in the Gulf, and the whole region is covered with surface waters of low salinity (less than 33°/₀₀). It is estimated that during the rainiest period the salinity of a 10-meter layer of water 300 miles long and 60 miles wide could be reduced by rainfall and runoff from 33 parts per mille to 28 parts per mille in a period of two to three months.

During the "Askoy" expedition, surface temperatures of 26° to 28° C. and surface salinities of somewhat less than 34 parts per mille were observed in most of the region. These high surface temperatures and relatively low surface salinities were characteristic of only a rather thin surface layer (reaching 25 meters or less) which was underlain by a shallow pycnocline. At 100 meters temperatures range from 15.8° to 19.5° C., salinities from 34.87 parts per mille to 35.05 parts per mille.

In the Gulf of Panama high surface temperatures, low surface salinities, and the presence of a strong shallow pycnocline suggest that upwelling in early 1941 was less intense than usual. This was confirmed by comparison with "Hannibal" observations in March, 1933, and by examination of long-term measurements of sea level and surface temperature at Balboa by the Panama Canal Company.

Correlation of a northerly wind-stress index for February–March with the average sea level for the same months over a 42-year period gave the significant correlation coefficient of −0.54. However, although the 1941 northerly wind-stress index was somewhat lower than average, it was not low enough to account for the unusually high sea level observed in 1941. Thus it seems likely that some other large-scale process affecting sea temperatures over a large area was operating.

During the first half of 1941 *El Niño* was observed off the coast of northern Peru. Schott's explanation of this phenomenon, based on its characteristics in 1891 and 1925, calls for a cold tongue extending from the Gulf of Panama nearly to the equator. Although this cold tongue was not detected by the "Askoy," unusually high temperature, low salinity, and a strong southward surface current measured west of Malpelo Island may be related to the influx of northern waters on the coast of Peru.

Observation of a pronounced subsurface temperature discontinuity 200 miles west of Buenaventura, accompanied by other indications at the surface, suggests that a well-developed oceanic front was present on March 24, 1941.

Examination of average surface current charts shows a northward coastal surface

flow north of Cabo de San Francisco throughout the year, with a mean speed of about 25 cm. per second (0.5 knot) and a width of less than 100 miles. "Askoy" measurements in the northern part of the Bight show a subsurface distribution of mass consistent with such a current which appears to be the eastern limb of the general counterclockwise circulation in the Panama Bight. It is proposed that it be called the "Colombia Current."

LITERATURE CITED

Beebe, W.
1926. The Arcturus oceanographic expedition. Zoologica, vol. 8, no. 1, pp. 1–45.

Bruneau, L., N. G. Jerlov, and F. F. Koczy
1953. Physical and chemical methods. *In* Reports of the Swedish deep-sea expedition 1947–1948. Göteborg, vol. 3, no. 4, pp. 99–112, pls. 1–55.

Carlsberg Foundation
1937. Hydrographical observations made during the "Dana" expedition 1928–30. *In* The Carlsberg Foundation's oceanographical expedition round the world 1928–30. Copenhagen and London, vol. 2, Dana-Report no. 12, pp. 1–46.

Cromwell, T.
1958. Thermocline topography, horizontal currents and "ridging" in the eastern tropical Pacific. Bull. Interamer. Trop. Tuna Comm., vol. 3, no. 3, pp. 135–164.

Cromwell, T., and J. L. Reid, Jr.
1956. A study of oceanic fronts. Tellus, vol. 8, no. 1, pp. 94–101.

Crowe, P. R.
1952. Wind and weather in the equatorial zone. Publ. Inst. Brit. Geogr., Trans. Papers, 1951, no. 17, pp. 23–76.

Discovery Committee
1949. Station list R.R.S. "William Scoresby" 1931–1938. *In* Discovery Reports. Cambridge, England, vol. 25, pp. 143–280, pls. 34–37.

Fiedler, R. H., N. D. Jarvis, and M. J. Lobell
1943. La pesca y las indústrias pesqueras en el Perú. Lima, Compañia Administradora del Guano, Lima, 371 pp.

Fleming, J. A., C. C. Ennis, H. U. Sverdrup, S. L. Seaton, and W. C. Hendrix
1945. Oceanography I-B. Observations and results in physical oceanography. Scientific results of Cruise VII of the "Carnegie" during 1928–1929, under command of Captain J. P. Ault. Publ. Carnegie Inst. Washington, no. 545, 315 pp.

Fleming, R. H.
1940. A contribution to the oceanography of the Central American region. Proc. Pacific Sci. Congr., Berkeley, 1939, vol. 3, pp. 167–175.

Garth, J. S.
1948. The Brachyura of the "Askoy" expedition, with remarks on carcinological collecting in the Panama Bight. Bull. Amer. Mus. Nat. Hist., vol. 92, pp. 1–66.

Godske, C. L., T. Bergeron, J. Bjerknes, and R. C. Bungaard
1957. Dynamic meteorology and weather forecasting. Washington, American Meteorological Society and Carnegie Institution, xvi+800 pp.

Hertlein, L. G., and A. M. Strong
1955. Marine mollusks collected during the "Askoy" expedition to Panama, Colombia, and Ecuador in 1941. Bull. Amer. Mus. Nat. Hist., vol. 107, no. 2, pp. 159–318.

Jacobs, W. C.
1951. The energy exchange between sea and atmosphere and some of its consequences. Bull. Scripps Inst. Oceanogr., vol. 6, no. 2, pp. 27–122.

Jones, S. M.
1950. Geology of Gatun Lake and vicinity, Panama. Bull. Geol. Soc. Amer., vol. 61, pp. 893–922.

Lobell, M. G.
1942. Some observations on the Peruvian Coastal Current. Trans. Amer. Geophys. Union, no. 2, pp. 332–336.

Manuel, G.
1955. Geografía de Colombia. Bogota, Libreria Stella, 200 pp.

Murphy, R. C.
1939. The littoral of Pacific Colombia and Ecuador. Geogr. Rev., vol. 29, pp. 1–33.
1941. The Askoy expedition of the American Museum of Natural History in the eastern tropical Pacific. Science, vol. 94, no. 2429, pp. 57–58.
1942. Pacific campaign of the schooner Askoy —Darien, Colombia, Ecuador. Trans. Amer. Geophys. Union, no. 2, pp. 336–338.
1944. To the Chocó in the schooner "Askoy." Nat. Hist., New York, vol. 53, pp. 200–208.

Nichols, J. T., and R. C. Murphy
1944. A collection of fishes from the Panama

Bight, Pacific Ocean. Bull. Amer. Mus. Nat. Hist., vol. 83, no. 4, pp. 217–260.

Palmer, C. E.
1951. Tropical meteorology. *In* Malone, T. F. (ed.), Compendium of meteorology. Boston, American Meteorological Society, pp. 859–880.

Posner, G. S.
1957. The Peru Current. Bull. Bingham Oceanogr. Coll., vol. 16, no. 2, pp. 106–155.

Riehl, H.
1954. Tropical meteorology. New York, McGraw-Hill, x+392 pp.

Schaefer, M. B., Y. M. Bishop, and G. V. Howard
1958. Some aspects of upwelling in the Gulf of Panama. Bull. Interamer. Trop. Tuna Comm., vol. 3, no. 2, pp. 79–132.

Schmidt, J.
1929. Introduction to the oceanographical reports including list of the stations and hydrographical observations. *In* The Danish "Dana" expeditions 1920–22. Copenhagen and London, no. 1, 87 pp.

Schott, G.
1931. Der Peru-Strom und seine nördlichen Nachbargebiete in normaler und anormaler Ausbildung. Ann. Hydrogr. u. Marit. Met., vol. 59, pp. 161–169, 200–213, 240–252.
1935. Geographie des Indischen und Stillen Ozeans. Hamburg, C. Boysen, xx+143 pp., 37 pls.

Schweigger, E.
1942. Las irregularidades de la corriente de Humboldt en los años 1925 a 1941. Una tentativa de su explicación. Bol. Compañia Administradora Guano, Lima, vol. 18, no. 1, pp. 27–42.

Sears, M.
1954. Notes on the Peruvian coastal current. 1. An introduction to the ecology of Pisco Bay. Deep-Sea Res., vol. 1, pp. 141–169.

Shumway, G.
1954. Carnegie Ridge and Cocos Ridge in the east equatorial Pacific. Jour. Geol., vol. 62, no. 6, pp. 573–586.
1957. Carnegie Ridge bathymetry. Deep-Sea Res., vol. 4, no. 4, pp. 250–253.

Spilhaus, A. F.
1938. A bathythermograph. Jour. Marine Res., vol. 1, pp. 95–100.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming
1942. The oceans, their physics, chemistry and general biology. New York, Prentice-Hall, x+1087 pp.

United States Department of Agriculture
1938. Atlas of climatic charts of the oceans. Weather Bureau, no. 1247, 130 charts.

United States Hydrographic Office
1934. Dynamic oceanographic data for the central eastern Pacific Ocean. Publ. no. 212, 53 pp.
1945. Weather summary, South America, northern and northwestern part. Publ. no. 528, 166 pp.
1947. The atlas of surface currents, northeastern Pacific Ocean. Publ. no. 570, 12 charts.
1952. Sailing directions for South America. Publ. no. 174, vol. 3, 392 pp.

Vogt, W.
1942. Informe elevado a la Compañia Administradora del Guano. Lima, Compañia Administradora Guano, vol. 18, no. 3, pp. 1–132.

Wooster, W. S.
[MS.] Shellback expedition, 17 May to 27 August 1952. Univ. California, Scripps Inst. Oceanogr., Ref. 52–63, 1952.

Wooster, W. S., and T. Cromwell
1958. An oceanographic description of the eastern tropical Pacific. Bull. Scripps Inst. Oceanogr., vol. 7, no. 3, pp. 169–282.

Wooster, W. S., and F. Jennings
1955. Exploratory oceanographic observations in the eastern tropical Pacific, January to March, 1953. California Fish Game, vol. 41, no. 1, pp. 79–90.

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Geology of the Pacific Sea Floor

By H. W. Menard*

Introduction

The oceans cover more than two-thirds of the surface of the earth and a knowledge of what lies beneath them is essential to understanding many of the great problems of geology. Are continents and ocean basins permanent? Do the continents move relative to each other? These problems have been recognized from studying the continents where data are complicated by the conflict between the internal forces which elevate the land and erosion which truncates it. Under the ocean, erosion is quantitatively insignificant compared to on land so that mountains retain the shapes given them by internal forces. Consequently submarine topography is nearly equivalent to ideal geological structures on land. Little was known of the relief of the Pacific sea floor before the last decade when oceanographic expeditions put to sea, with sounders capable of reaching any depth. Since then the Scripps Institution of Oceanography and Navy Electronics Laboratory have sounded more than 500,000 km of track (Fig. 1). These soundings and related geophysical observations form the main basis for the present discussion although Russian oceanographers have sounded for comparable distances, and the Swedish *Albatross*, and Danish *Galathea*, and British *Challenger II* expeditions have also made major contributions to knowledge of the Pacific basin.

The topography of the ocean floor has a broad reticulate pattern of elevations and depressions and characteristically the center of each ocean basin is relatively shallow. The elevations and depressions compare in size with small continents or large complexes of mountains such as the complex extending from the Mediterranean to the East Indies. Superimposed on these broad features are deep trenches, linear archipelagoes, and fracture zones, all of which have the dimensions of individual mountain ranges, *e.g.*, the Alps or Himalayas. The relief more subdued than a whole mountain range is only partially known at present. However, it appears that the sea floor is irregular with volcanoes and low hills of undetermined origin except where turbidity currents or very fluid lava flows have buried the hills and formed smooth plains.

The various kinds of topography will be considered starting with the largest. Particular emphasis is placed on seamounts, abyssal plains, fracture zones, and other features which were not known to exist only 15 years ago.

Broad Elevations and Depressions

The greatest topographic feature of the sea floor is an essentially continuous median elevation which extends through the Atlantic, Indian, Antarctic and South Pacific Oceans for a total distance of about 30,000 km[1]. The relief of the elevation above the adjacent basins is 1–3 km and the width in most places is more than 1000 km. This elevation is conspicuously centered in the Atlantic and Indian Oceans where it is called the Mid-Atlantic and Mid-Indian Ridges. In the South Pacific the position relative to the margins of the basin is less obvious but it can be determined by an arbitrary method (Fig. 2). The technique used is to accept the 1000 m isobath as the margin of the ocean basin and to draw a family of lines approximately parallel to and equidistant from the margin by swinging arcs on a globe[2]. The intersections of arcs with equal radii are connected to establish median lines. Consequently any major convexity of the margin of an ocean basin has a median line in addition to the one for the whole basin. The great curve bounded by New Guinea, the Phillipines and Japan is an example of such a convexity in the Pacific.

This method of geometrical construction shows that the crest of the East Pacific Rise lies near the median line between New Zealand and Antarctica but at about 55° S. latitude the crest bends sharply to the east and is about 1000 km east of the median line from the bend to Easter Island. Apparent fault scarps suggest that the bend is an offset caused by faulting or else a discontinuity at the margins of large crustal blocks. A similar bend or discontinuity in the East Pacific Rise near Easter Island occurs where an east-west zone of fracturing intersects the rise.

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[1] M. Ewing and B. C. Heezen, Geophys. Monogr. *1*, 75 (1956)

[2] H. W. Menard, Bull. Geol. Soc. Amer. *69*, 1179 (1958)

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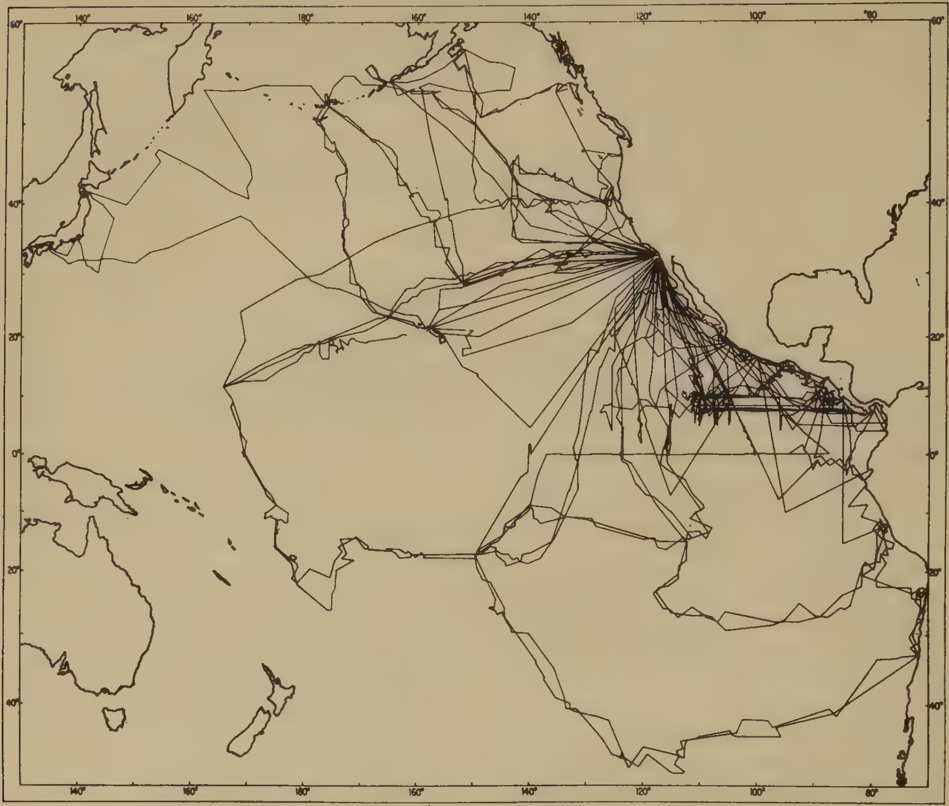

Fig. 1.—Sounding lines of the Scripps Institution of Oceanography and the Navy Electronics Laboratory, 1950–1958. Echograms along these tracks provide most of the evidence discussed.

It is only in the central and North Pacific that an obvious correlation between a geometric median line and a broad median elevation is not found. However, there is a correlation with another type of submarine topography – long, narrow, steep-sided ridges capped with atolls and seamounts. The median line of the whole basin trends northwest from Easter Island through the Tuamotu Islands and the Line Islands to Johnston Island. The Tuamotu Ridge has an area of 200,000 sq km shoaler than 3 km and about 100 atolls and seamounts rise above the ridge. Some of the seamounts are guyots or former islands which are now submerged. The Line Islands rise from the Christmas Island Ridge which also has an extensive area of perhaps 100,000 sq km above 3 km depth and many seamounts and guyots between the islands.

From Johnston Islands the median line has three spurs. The north-eastern spur is not related to any conspicuous topography. The northern spur lies somewhat east of but parallel to the Emperor Seamounts which are a line of large guyots rising from a ridge with about 1 km relief. The western spur corresponds to the Marcus-Necker Rise which, in its eastern half, the Mid-Pacific Mountains[3], has an area of 60,000 sq km shoaler than 3 km. The Mid-Pacific Mountains include about 50 seamounts, mostly guyots, distributed broadly over the ridge. The wholly submerged Mountains and the Tuamotu Archipelago bear a close resemblance in every detail of topography except that the ancient islands of the Mid-Pacific were not capped by reef corals which grew upward as the islands subsided.

The median elevations in most places in the ocean basins are broad gently sloping rises but in the central and North Pacific they are narrow and steep sided. Do these different types of topography represent different stages in development? If they do, the broad rises are an early stage and the narrow ridges are a later one.

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[3] E. L. HAMILTON, Geol. Soc. Amer. Mem. *64* (1956).

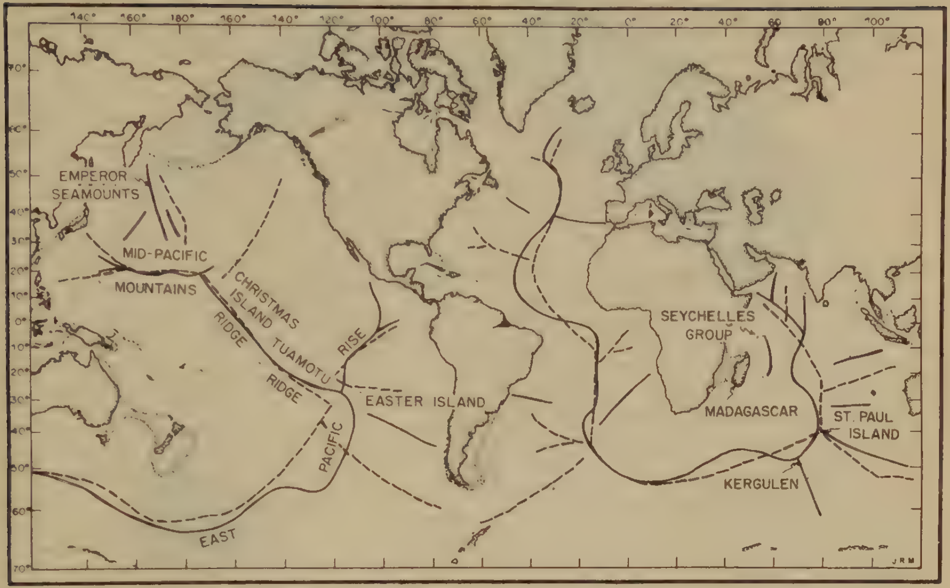

Fig. 2. – Location of the crests of submarine median ridges and rises (solid line) compared with the geometrical median line (dashed) of the ocean basins. Points on the geometrical median line are equidistant from the margins of the continents as indicated by the 1000 isobath which is shown by dotted shading where it does not almost coincide with the shore line and where it is pertinent to the construction.

This is shown by the fact that the broad rises are the locus of a continuous narrow band of earthquakes and active or recently extinct volcanoes. In addition, the heat flow from the earth is highly variable under broad oceanic rises suggesting that very powerful deforming forces are active. The central and North Pacific narrow ridges show no such signs of crustal instability. There are no earthquakes, active volcanoes, or abnormal values of heat flow. On the contrary, deep guyots and atolls bear witness to long-continued quiescence and subsidence.

Abyssal Plains. The floors of many broad oceanic basins are extremely smooth, gently sloping abyssal plains. These plains were discovered about 10 years ago when continuously recording echo sounders became available. Their origin was disputed for several years but, at present, every line of evidence available suggests that they were produced by turbidity currents spreading out on the sea floor from the continents. (1) The plains contain coarse sands and anomalous shallow water fossils which can have been transported only by turbidity currents[4]. (2) The sediment under abyssal plains is several times thicker than is normal in oceanic basins, indicating relatively rapid deposition[5]. (3) Throughout the world abyssal plains occur only where turbidity currents spreading from continents are not barred by bottom topography[6]. Thus they are widespread in the Atlantic but relatively rare in the Pacific because turbidity currents cannot flow past island arcs and trenches. (4) The small scale relief of the plains and their approaches can be explained only by the action of bottom moving turbidity currents[7]. Submarine canyons cut in the continental slope lead out to deep-sea fans which in turn are crossed by channels that extend for some distance on the abyssal plains. In short there are all the elements of a drainage system reaching to a depth of more than 5 km.

An enormous turbidity current apparently swept down from the Grand Banks area off Newfoundland and broke a large number of submarine cables in 1929[8]. Ancient turbidity currents of this scale have been reported as existing in the geological record and they may be relatively common in some places and at some times. However, off central California almost all the deposition by turbidity currents has been in great fans at the mouths of submarine canyons. Turbidity currents rising from slumps on the continental slope between the canyons have played a very minor role in shaping the topography. In this region the sediment available to turbidity currents apparently is dumped into the heads of submarine canyons by long-shore drift. Thence the sediment slumps into the canyons and emerges on the fans in turbidity currents.

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[4] D. B. Ericson, M. Ewing and B. C. Heezen, Bull. Amer. Assoc. Petrol. Geol. *36*, 489 (1952).

[5] C. B. Officer, Deep-Sea Research *2*, 253 (1955).

[6] H. W. Menard, Coll. Internat. Cent. Nat. Res. Scientifique *83* (1958).

[7] H. W. Menard, Bull. Amer. Assoc. Petrol. Geol. *39*, 236 (1955).

[8] B. C. Heezen and M. Ewing, Amer. Journ. Sci. *250*, 849 (1952).

Features with the Scale of Mountain Ranges

Oceanic Trenches and Island Arcs. Trenches and island arcs were among the first surveyed features of oceanic topography because they were barriers to submarine cables. The island arcs include lines of active volcanoes and they are associated with more large earthquakes and more pronounced gravity anomalies than any other part of the earth's crust. The more or less arcuate trenches which border them are the deepest places in the oceans, which is particularly noteworthy because they are at the edges of ocean basins rather than the middle. At present the greatest depth known is about 10,600 m in the Marianas Trench but very similar depths have been found in the Kurile and Tonga Trenches[9]. Relatively recent investigations of trenches have shown that the shallower trenches in the Caribbean Sea and on the eastern side of the Pacific are partially filled with sediment and, in places, have very flat bottoms. Field seismic methods give equivocal results and it is not yet certain whether the crust under all trenches has been bowed downward to form a root under the trenches. It appears, however, that a small root exists under some Pacific trenches[10]. This point is critical if oceanic trenches are equivalent to geosynclines which are downbowings of the crust representing the earliest stage in the formation of mountain ranges on the continents. Heat flow has been measured along the axes of two trenches and found to be abnormally low. This has been interpreted as suggesting that the downward limb of a convection current exists in the mantle under the trenches[11]. If so, the convection current may be pulling the crust downward to form the trench.

Fracture Zones. Fracture zones are long thin bands that are conspicuously more mountainous than the sea floor in general and which ordinarily separate regions with different depths[12]. The first wholly submarine fracture zones were discovered only a few years ago in the northeastern Pacific Basin. There they are four great bands which are approximately parallel but individually three of them follow great circles (Fig. 3). Each is about 100 km wide and more than 2000 km long. Within the zones are asymmetrical ridges and narrow troughs which are parallel to the general trend. Large volcanic seamounts are also common. The Murray fracture zone may be taken as an example. It extends along the sea floor in an easterly direction from near the Hawaiian Islands to Southern California for about 3000 km. The western section of the zone is composed of two asymmetrical mountain ranges with the steep sides facing and a band of narrow troughs and ridges between. The total relief in a cross section 100 km wide is about 1600 m and most of the changes in depth are abrupt. South of the mountainous ridges and troughs and parallel to them is a great range of submarine volcanoes called the Moonless Mountains because none of them have ever been above sea level although several are more than 3000 m high. In the central section of the Murray fracture zone the northern asymmetrical mountain range disappears and the relief of the southern range becomes greater. In addition a regional change in depth appears such that the sea floor for hundreds of km north of the fracture zone is about 400 m deeper than the sea floor for an equal distance to the south. A single seamount rises above the crest of the range to give a local relief of 4750 m. This seamount, called Erben Guyot, has a flat top from which beach gravels and fossils have been dredged[13]. Although it is now 450 m beneath the sea surface, it apparently was an island sometime more than twenty million years ago. In the section of the Murray fracture zone nearest the continent the relief becomes more subdued but there are several short troughs more than 500 m deep and the regional change in depth still exists. A seaborne magnetic survey of this region shows a north-trending pattern of anomalies with magnitudes of about 500 γ[14]. The anomaly pattern is disturbed along the east-trending line of the Murray fracture zone. The pattern can be matched on opposite sides of the disturbance and it appears that it has been offset 150 km which would make it one of the largest fault displacements known. The Transverse Ranges of California lie on the trend of the Murray fracture zone and, at least superficially, they seem to be an extension of the zone.

In addition to the original four, there may be other fracture zones which have not yet been discovered. They are difficult to detect without continuously recording echo sounders and they cannot be confirmed without special surveys. The locations of some suspected fracture zones are shown in Fig. 3. They are suggested by more or less fragmentary evidence from random sounding lines.

Linear Archipelagoes. That the island groups of the Pacific basin lie along straight lines has long been recognized as geologically significant. Modern oceanographic exploration has added little information about the islands except to show that there are similar groups

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[9] R. L. FISHER and R. REVELLE, Sci. Amer. *193*, 36 (1955).

[10] R. W. RAITT, R. L. FISHER and R. G. MASON, Geol. Soc. Amer. Spec. Pap. *62*, 237 (1955).

[11] E. C. BULLARD, A. E. MAXWELL and R. REVELLE, Adv. Geophys. *3*, 153 (1956).

[12] H. W. MENARD, Bull. Geol. Soc. Amer. *66*, 1149 (1955).

[13] A. J. CARSOLA and R. S. DIETZ, Amer. Journ. Sci. *250*, 481 (1952).

[14] R. G. MASON, Geophys. Journ. in press.

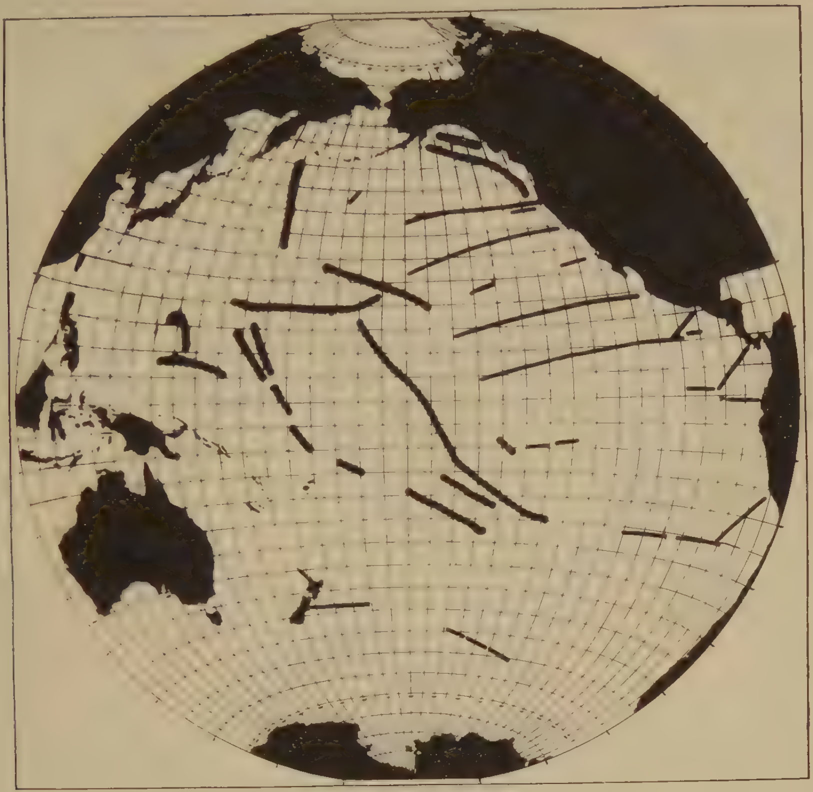

Fig. 3.—Fracture zones and suspected fracture zones of the Pacific Basin (solid lines) compared with linear island archipelagoes including guyots.

of marine volcanoes which are wholly sugmerged and that some of the seamounts formerly were islands. The deep sea floor in the vicinity of island groups has been relatively unknown until recently, however, and it has proved rewarding to study.

Most linear island groups such as the Hawaiian, Marquesas, Samoan, and Society Islands stand above a high ridge which may be caused, in small part, by faulting but appears to be explainable solely as the result of piling up of lava flows between closely spaced volcanoes. Some linear groups, including the Austral Islands, are relatively isolated volcanoes rising directly from the deep sea floor. The volcanoes of the latter groups are too widely spaced or have not been productive enough to pile up lavas between them and build a ridge.

Although they are linear on a small scale map, the archipelagoes in detail are spread in a band that may be one-fourth as wide as the length if adjacent large seamounts are included with the islands. Consequently they mark a zone of weakness in the crust rather than a single major fault. The center of volcanic activity appears to migrate in a regular manner from one end of some zones of weakness to the other[15]. An outstanding example of the apparent shifting is the Hawaiian Archipelago where the former volcanoes at the northern end are now atolls, the central section is made up of inactive volcanoes, and the southern end has active volcanoes. The Austral Islands and the drowned Mid-Pacific Mountains have had a more complicated history with at least two periods of vulcanism. Sprinkled among the Austral Islands are five guyots at depths of 1100–1500 m. Clearly they are former active volcanoes which were islands but which became inactive and subsided long before the period of vulcanism in which the existing islands were formed.

The enormous load of a group of volcanic islands might be expected to depress the crust of the earth, and a moat, or encircling depression, around the

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[15] L. J. Chubb, Geol. Mag. 94, 221 (1957).

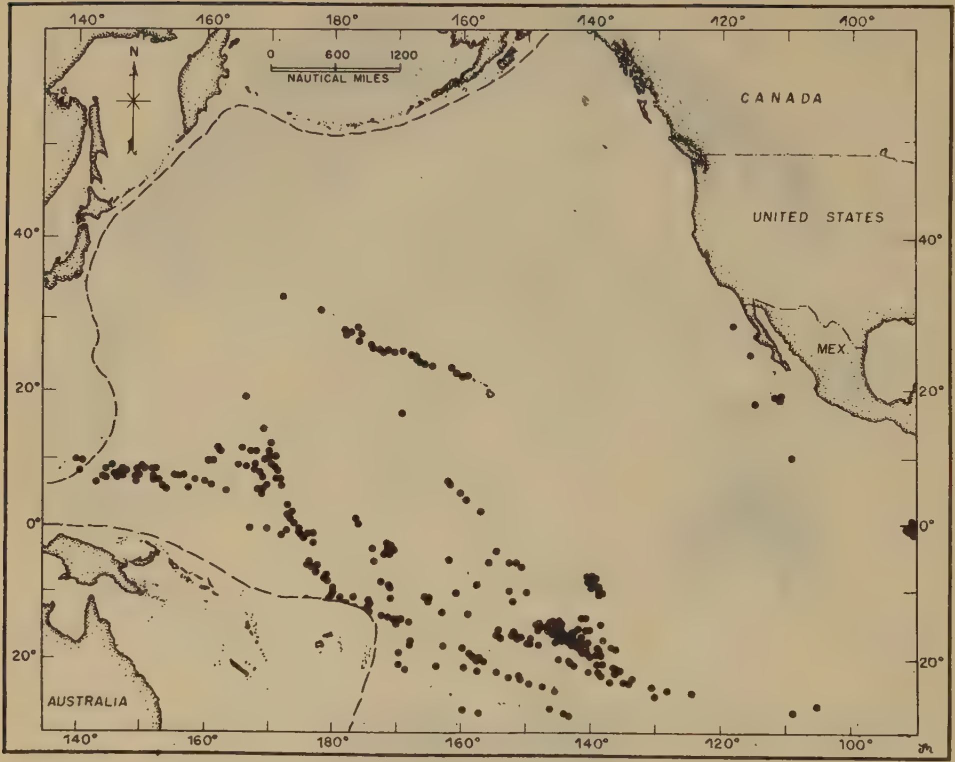

Fig. 4.—Islands including atolls rising from volcanic platforms.

southern Hawaiian Islands has been attributed to this cause[16]. The moat is only slightly deeper than average for the region, but it in turn is encircled by a broad arch which makes the moat more conspicuous. Most archipelagoes are not encircled by moats that are evident in the topography of the sea floor. However, abnormal thicknesses of several kilometers of volcanic rocks lie under the sea floor in the vicinity of many archipelagoes[17]. Inasmuch as the sea floor is not elevated, the upper surface of the crust must be depressed in a moat which has been filled predominantly with lava flows. The fill is called an 'archipelagic apron' and volume considerations suggest that most of the material has flowed from fissures on the deep sea floor[18]. However, some percentage of the fill has spread from the large volcanic islands, both in the form of flows and erosion products. Almost all archipelagic aprons have a very smooth upper surface, which is strikingly different from the normal abyssal hills of the deep sea floor, and this criterion has been used to identify the fill where sub-bottom observations are not available. The smooth surface and extremely gentle slopes indicate that the mode of spreading of erosion products is in turbidity currents. Bermuda Island is surrounded by a very thick apron but the surface is not smooth. In this case a formerly smooth apron may have been deformed into abyssal hills. However, Bermuda Island is a quantitatively trivial source for erosion products and it is possible that the material available has never been sufficient for turbidity currents to produce a smooth apron surface.

A startling recent discovery illustrates how little is known about the relief of the deep sea. The Hawaiian Islands are the focus of a very large number of sounding lines by naval vessels and several reconnaissance studies have been made by research ships with recording echo sounders. Nevertheless a major element of the sea floor topography completely escaped notice until a survey was made with closely spaced sounding lines positioned with precision electronic equipment

[16] R. S. Dietz and H. W. Menard, Journ. Geol. *61*, 99 (1953).

[17] T. F. Gaskell, Proc. Royal Soc., Ser. A 222, 356 (1954).

[18] H. W. Menard, Bull. Amer. Assoc. Petrol. Geol. *40*, 2195 (1956).

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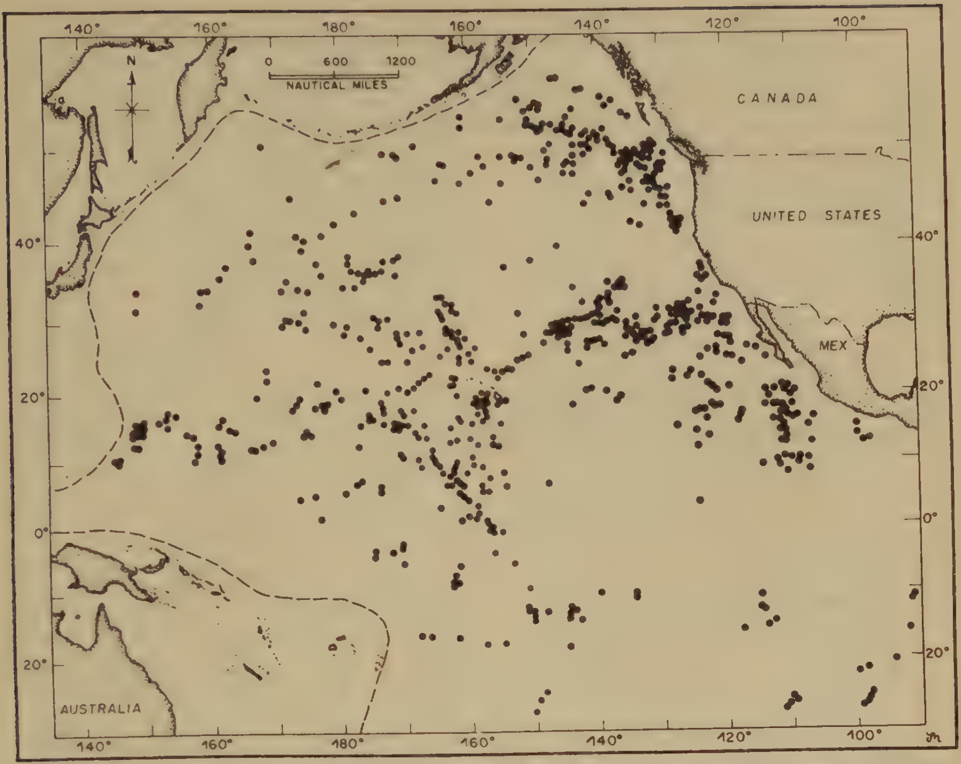

Fig. 5. — Known seamounts other than known guyots with more than 1 km relief. Most seamounts have not yet been discovered. The distribution shown reflects the density of sounding. The dots indicating location are larger than the individual seamounts.

not previously available. Narrow asymmetrical mountains 1–2 km high and 100–200 km long have been found in abundance on the Hawaiian Arch. They form a distinct pattern trending northeasterly on the east side ot the Hawaiian Islands, and southerly on the west side. Similar mountains do not occur on the arch where it curves around the end of the Hawaiian structure.

Seamounts and Abyssal Hills

A seamount differs from an abyssal hill by definition in that the former has more than 1 km of local relief. The dividing line of the two types is arbitrary but two kinds of features may actually exist. Numerous surveys and dredge hauls have established that almost all seamounts are volcanoes and the remainder are fault blocks. Abyssal hills appear to be the same landforms but very few have been surveyed and hardly any have been dredged. Hills have been cored and many have unconsolidated Tertiary sediments at the surface. More recent sediments apparently have migrated off the hills leaving the older sediments exposed. It has been suggested that the migration was caused by uplift of the hills which, judging by their shape, implies doming by laccolithic intrusions. Consequently it is not certain that all abyssal hills and seamounts are features of different sizes but the same origin.

The number of seamounts in the sea is of interest in geotectonics and it can be estimated in the Pacific by several methods with converging results. In the central Pacific Basin as defined by the andesite line there are about 400 islands (Fig. 4) that have volcanoes as a base, and about 1000 known seamounts with a relief of more than 1 km (Fig. 5). By rough approximation, about one-tenth of the area is sounded which implies that nine-tenths of the seamounts are undiscovered. A more quantitative estimate is based on statistical analysis of continuously recorded echo soundings which may be considered as random profiles of the bottom. For ease of analysis it is assumed that the seamounts of all sizes are cones with uniform slopes and that they are randomly distributed. No great error is introduced by the first assumption, but the second limits the size of the region that is studied because some topographic

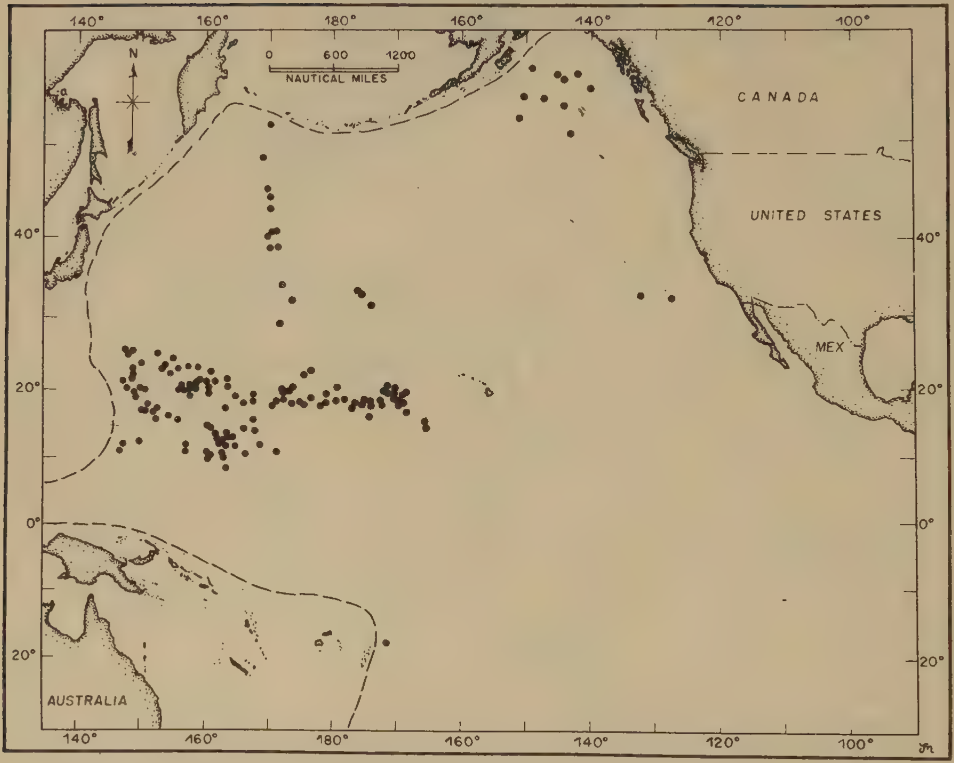

Fig. 6.—Guyots or flat-topped seamounts which were once islands but are now deeply submerged. Compare with the distribution of existing islands (Fig. 4).

provinces have more seamounts than others. The Baja California Seamount Province was selected and the width and height of all elevations higher than 400 m were measured on echograms of 7400 km of track in an area of 1,400,000 km^2. About 10^3 seamounts with at least 1 km relief appear to lie in the area, or about 1 per 1400 km^2. Extrapolating to the whole Pacific Basin and considering various sea floor topographic provinces, the total number would be of the order of 10^4. A third method of estimating is to count the seamounts in the only areas that are sounded densely enough to find every seamount and extrapolate to the remainder of the basin. The same value of 10^4 results.

The distribution of large seamounts and volcanic islands is not uniform; instead they are clustered in groups of ten to a hundred. Abyssal hills are randomly distributed, however, so that all of the sea floor has been the site of vulcanism, intrusions, or faulting. The vulcanism has ranged in geological time at least from the Late Cretaceous to the present day and it seems to have been concentrated in different areas at different times. This is indicated by the distribution maps of guyots (Fig. 6) and existing islands. At present, oceanic islands are concentrated in the southwestern Pacific whereas in the past they were also common in the northwestern part.

Tectonic Intensity in the Pacific Basin

The Pacific Basin within the andesite line is generally aseismic and the number of active volcanoes or even of volcanic islands is small. For these reasons it commonly is generalized that the basin has been a stable area in geological time. Modern oceanography has shown that the basin is covered with volcanoes and broken in many places by enormous faults so that it cannot always have been stable. The question raised is whether the present is abnormally quiet tectonically or whether geological time is adequate to produce the volcanoes and faults in a relatively stable basin. The answer depends to a large extent on the time available.

The demonstrable history of the Pacific Basin based on samples is very brief. Cores penetrate only a small distance and could hardly be expected to reach very ancient sediments, even though Tertiary outcrops occur. Dredge hauls of seamounts might sample material of any age because most submarine elevations are swept clean of sediment. To date Cretaceous fossils are the oldest ones sampled[19] but fossils of any kind are rare in dredge hauls and the basalt usually dredged is undatable. The potassium-argon method is capable of dating fresh basalts but the dredge can break off only weathered material unless the dredger has extraordinary luck. If present sampling is considered to be adequate, the Pacific Basin is no older than Cretaceous. However, further sampling may indicate greater age and it seems more logical to assume that the basin is as old as the continents.

As to faulting it can only be concluded that in the past earthquakes have been widespread in the Pacific Basin although not necessarily concentrated in time. The only alternative is to assume that the oceanic type of crust can be faulted without earthquakes and this is not acceptable because large earthquakes occur in a few places with an oceanic crust.

For intensity computations large volcanoes may be considered to lie in clusters of perhaps 20 and the life of a group estimated as of the order of 10^6–10^7 years. For 10^4 volcanic seamounts there are 500 clusters. Granting an age of 3×10^9 years, the rate of formation of clusters averages only $1/6 \times 10^6$ years. Only one cluster need be active at a time and the present vulcanism with four island groups active would be much higher than normal. On the other hand if the time available is only 10^8 years the rate of formation of clusters averages $1/2 \times 10^5$ years. For an average life of 10^7 years, 50 clusters would be active at one time which is far in excess of the present rate. For an average life of 10^6 years the rate would be the same as at present. Within the accuracy of the estimates it appears all the large volcanoes of the Pacific Basin could have been produced since Cretaceous time at the present rate of vulcanism.

Permanence of Ocean Basins and Land Bridges

Recent geophysical evidence reveals that ocean basins are profoundly different from continents. A continent cannot be changed into an ocean basin without changing 35 km of one type of rock into 5 km of another type and lowering the surface by 5 km. The reverse change would be equally difficult but there is no reason to believe that continents cannot be built outward into ocean basins by sedimentation and orogeny.

Nevertheless, the biological evidence for former connections between what are now widely separated continents can be explained without violating geophysical evidence that continents have not subsided within ocean basins. The continents may have moved like ships through the ocean basins, the oceans may have been shallower, or the sea floor may have been elevated and then subsided. Paleomagnetic measurements suggest that some continental drift has occurred but not that the continents around the Pacific Basin have ever been much closer together. Consequently one of the other possibilities seems to be required. Numerous guyots and atolls indicate that island stepping stones may always have been present in the basin. Along a line extending through the Mid-Pacific Mountains, the Line Islands, and the Tuamotu Archipelago the guyots and atolls generally have very little local relief but rather rise from large steep-sided ridges. When the guyots and atoll platforms were at sea level, the tops of the ridges formed three relatively shallow banks each more than 2000 km long. If the banks and islands were contemporaneous, they would have formed a bridge for shallow-water and land organisms that almost spanned the Pacific. There is no direct evidence bearing on the question of contemporaneity and probability in the matter depends somewhat on the process which formed the ancient islands.

The sea floor becomes shallower or is elevated in a sense if a group of volcanoes grows upward and forms islands. It is deepened if the volume and depth of the oceans increase because of the accretion of juvenile water. Vulcanism and accretion of water, therefore, can produce guyots. Alternatively, a section of the oceanic crust may be pushed upward by expansion of the mantle and seamounts may become islands. If the mantle contracts, the islands subside. This alternative mechanism may be the one which has produced the existing broad rises of the ocean basins because in several places the rises have the normal oceanic crustal thickness of about 5 km and the elevation apparently is caused by some process in the mantle. Present day median elevations are extremely long. If the guyot-capped ridges of the central Pacific are the ruins of an ancient median elevation they may well have been contemporaneous.

Zusammenfassung

Als Folge von Faltungen und vulkanischen Vorgängen, die in grossem Maßstabe ablaufen, ist der Meeresboden meistens gebirgig. Lokal dagegen erscheint der Boden flach, da die Berge unter Ebenen sedimentären oder vulkanischen Ursprungs verborgen sind.

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[19] E. L. Hamilton, Geol. Soc. Amer. Mem. *1956*, 64.

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TWO NEW GENERA OF DINOFLAGELLATES FROM CALIFORNIA[1]

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The coastal waters in the San Diego region support fairly abundant populations of phytoplankton. Armored dinoflagellates of this region were studied extensively by Kofoid and his associates (1907–1933), but there are still numerous undescribed or little known representatives especially among the smaller species. In the present paper, two new genera and species are described. These were originally isolated by Dr. Beatrice M. Sweeney in 1956–57 from coastal water at La Jolla, Calif., and have since been maintained as laboratory cultures.

Acknowledgment is here made to Prof. Francis T. Haxo and Prof. Martin W. Johnson for their interest and for providing research facilities. The author is indebted to Dr. Beatrice M. Sweeney whose cultures made this study possible, to Mrs. Anne Dodson for valued technical aid and to Dr. K. A. Clendenning for assistance in the preparation of the manuscript.

METHODS

The dinoflagellates were first examined alive. Fixed material was then studied under an oil immersion objective and by phase contrast. To derive the general plate formulae of the thecae, an individual cell was isolated under a cover-glass. A drop of concentrated sodium hypochlorite solution was then passed slowly under the cover-glass to destroy the protoplasm and to remove the cement which unites the plates. This process was assisted by applying very gentle pressure to the cover-glass, but great caution was necessary because of the fragility of the specimens. With *Scrippsiella*, it proved helpful to store droplets of the cultures in a wet chamber for a few hours. Under these conditions many of the cells shed their thecae, to which the hypochlorite treatment was then applied. After testing other methods, the following technique was adopted for the examination of *Fragilidium*. Actively swimming individuals were killed by transferring them into 5% formaldehyde with a micropipette. Individual specimens were next isolated, and by applying gentle pressure to the cover-slip, the protoplasm was

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[1] Contribution from the Scripps Institution of Oceanography, New Series. 1087

[2] Permanent address: Casilla de Correo 64, Necochea, Argentina. This work was conducted during the tenure of a John Simon Guggenheim Fellowship, 1957–58, at the Scripps Institute of Oceanography, University of California, La Jolla.

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Scrippsiella sweeneyi n. gen., n. sp.

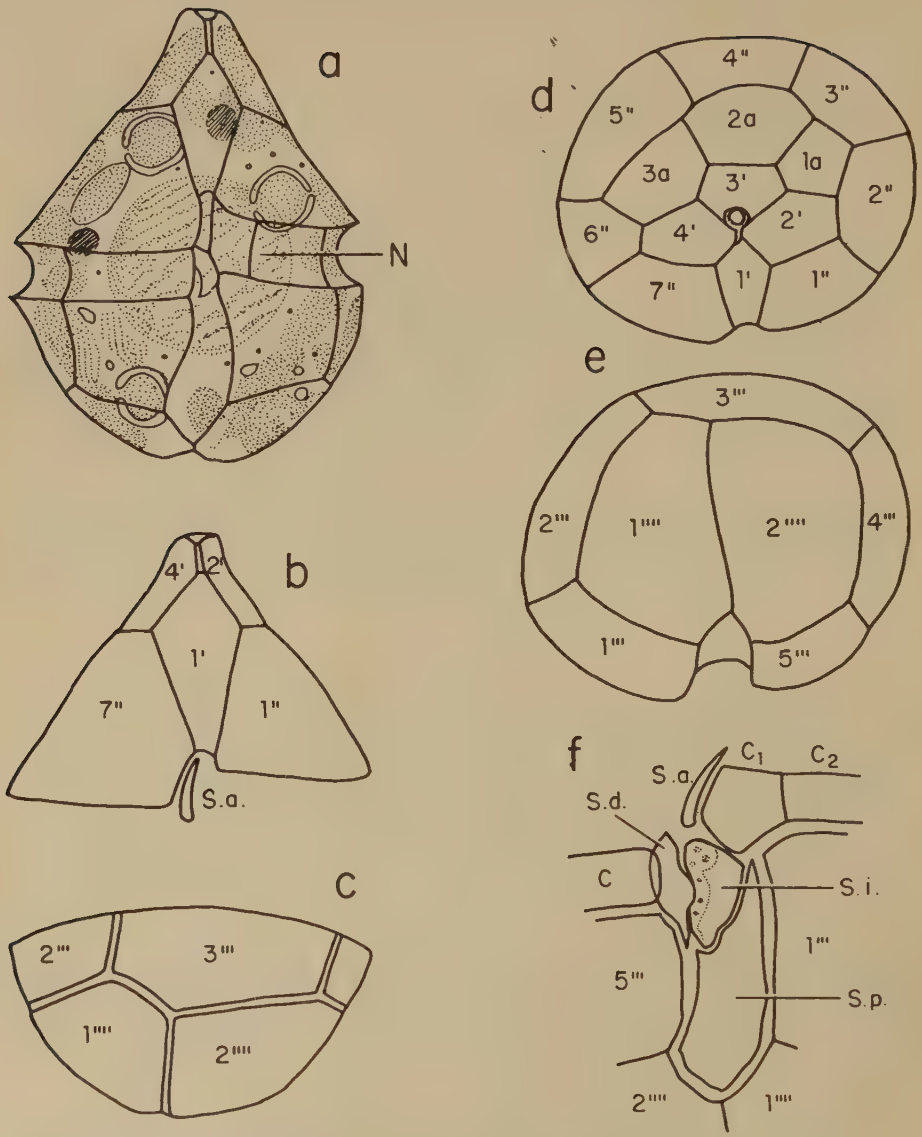
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FIGURE 1. *Scrippsiella sweeneyi.* a) A typical individual, ventral view. b) Ventral view of the epitheca. c) Dorsal view of the hypotheca. d) Apical view of the epitheca. e) Antapical view of the hypotheca. f) Sulcal region (S.a.: Anterior sulcal.—S.i.: left sulcal.—S.d.: right sulcal.—S.p.: posterior sulcal). All figures about × 1500.

forced out of the theca through the cingular region. The hypochlorite treatment was then applied to the empty *Fragilidium* theca, especially in studies of the sulcus and cingulum.

Diagnosis. Small-sized, conical epitheca, rounded hypotheca, without horns. Cingulum wide, cavazone, descendent, with displacement equal to two-thirds of its width, without lists. The cingulum has six plates, five equal, preceded at the left by a transitional one. Sulcus deep, of medium width, slightly curved to the right. The sulcus has four plates, with the posterior plate largest. The pattern of the major body plates is the same as that of an *Orthoperidinium* with three intercalaries. Cell length, 24–32.5 μ; transdiameter, 19–24 μ, chromoplasts numerous, elliptical, generally brown-yellow. La Jolla, California.

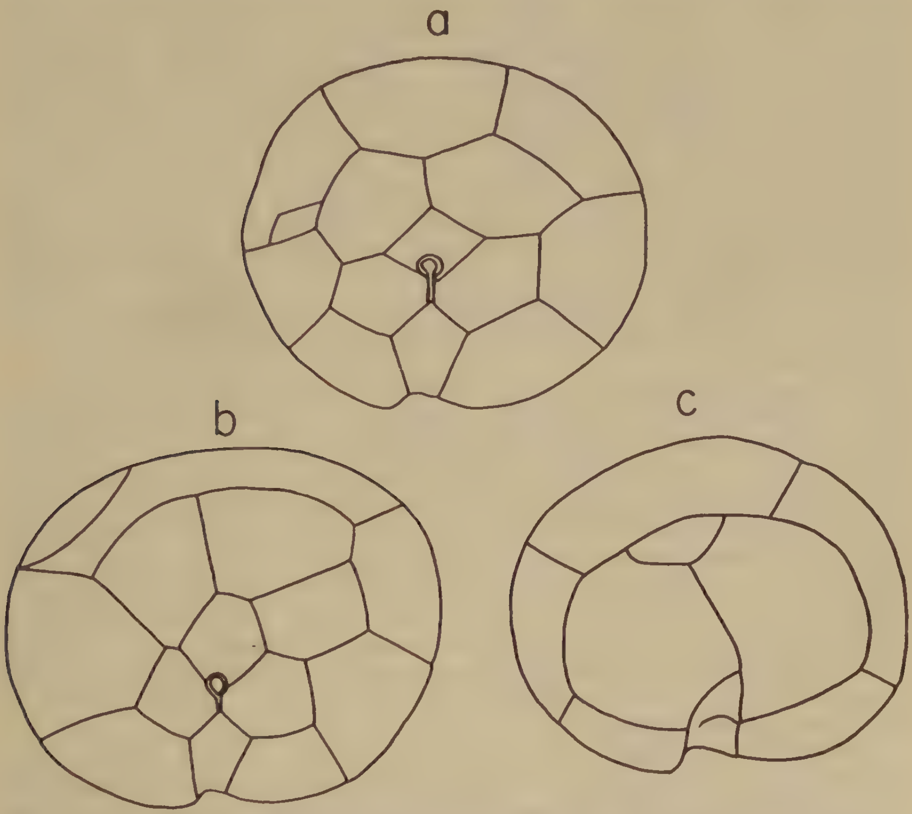

FIGURE 2. *Scrippsiella sweeneyi*, atypical plate patterns. a and b) Two epithecae, apical view. c) Antapical view of a hypotheca. All figures about × 1500.

Description. This organism resembles *Peridinium trochoideum* in its general shape and size, and to some degree in its plate formula: 4′, 3a, 7″, 6c, 5″ ′, 2″ ″, and 4s. Its epitheca is high and conical, most individuals deviating from a rectilinear outline by a concavity near the apex, as shown in Figure 1a. The hypotheca is almost hemispherical, and slightly shorter in length than the epitheca. In the region of the girdle, there is a slight dorsiventral compression. In apical view, the cells normally appear almost circular. The sulcus indents slightly into the epitheca, is very deep, and of medium width. It does not reach the antapex when in true frontal view.

The plate pattern of the major body plates is the same as that of an *Orthoperidinium* with three intercalaries. In the epitheca, the first apical plate (1′) is very narrow, with an asymmetrical rhombic shape and upwardly curved base. Attached to its anterior end, there is an extremely narrow ventral apical plate. The apex of the theca is horizontal, and is closed by a circular plate (apical pore platelet) which indents the pentagonally shaped third apical plate (3′). Plates 2′ and 4′ are comparatively large, and generally 2′ is a little wider than 4′. There are three dorsal intercalaries. Plate 2a is usually pentagonal but is sometimes hexagonal.

In the hypotheca, there are five post-cingulars and two antapicals. Plates 1″ ′ and 5″ ′ are wide, and 3″ ′ is very asymmetrical; its border with 2″ ″ is very long in comparison with its border with 1″ ″. The two antapicals have a very restricted connection with the end of the sulcus.

The cingulum has five plates of similar size, plus a transitional plate at the left end which is somewhat different in shape and also a little higher than the other cingular plates.

The sulcus of dinoflagellates is not easily examined, and has been neglected by most protistologists for that reason. The sulcus of *Scrippsiella sweeneyi* is exceptionally difficult to analyze, being about as difficult to study as that of *Heterocapsa triquetra*. The anterior sulcal plate (S.a.) is narrow and a little curved. It borders 7″. Posterior to this plate are two smaller plates (S.i. and S.d.). The shorter and broader of these two is the left plate (S.i.), which extends very slightly beyond the distal end of the girdle. The right border of this plate (S.i.) is thickened and refringent; it is provided with poroids and at the extreme anterior end there are two closely spaced pores. The right sulcal plate (S.d.) narrows toward the posterior. The posterior plate (S.p.) is the largest, forming the greatest part of the sulcus. Its right anterior border is strongly oblique to the axis of the plate and articulates with S.i. The posterior right border of S.p. is thickened.

The nucleus is round and located at the girdle level. Its diameter is about one-third of the total cell length. The chromatin strands are less evident than in most dinoflagellates. The chromoplasts are elliptical and numerous, sometimes yellow-green but normally brown-yellow. Food is apparently stored as small granules and also around the chromoplasts in bodies that resemble pyrenoids. There is no pusule nor stigma.

The first external evidence of cell division is the formation of two discrete longitudinal flagella with separate points of attachment. During division, the cell escapes from the theca but retains a tough cellular membrane. The two daughter cells remain attached to each other in an oblique plane. The posterior cell is usually the smallest.

Locomotion is normally rapid, with a strongly rotatory motion. There is usually one complete rotation of the organism during an advancement of one or two cell lengths. Sometimes, when *S. sweeneyi* cells reach the border of a drop, they suddenly cast off their flagella. Generally they lose the transverse ribbon-like flagellum first, which continues to beat in the detached state for a few seconds and then vacuolizes. The longitudinal flagellum is about three times as long as the cell; it does not beat or vacuolize after detachment.

Occurrence. This organism was originally isolated on March 15, 1956, from water collected off the S.I.O. pier at La Jolla, California, and has since been observed frequently in locally collected water samples. It seems to be a year-round inhabitant of the San Diego region, thriving especially in the summer months. This species has also been observed in plankton net samples, its relative scarcity in these being caused by its small size and poor retention on plankton silk.

Variations. The cingular and sulcal formula has been constant in laboratory and field specimens: 6C and 4S. The cells varied in size, and in the laboratory clonal culture used in the description, the cells also varied in shape and in plate pattern. Deformed or aberrant forms of *S. sweeneyi* were numerous in old laboratory cultures, but these were not observed in plankton samples. The plate formulae of the thecae from plankton samples were established in only a few cases, so we do not yet know how much the plate formula of this organism varies in nature. On the whole, the plate pattern has shown an amazing range of variation.

The normal plate formula is as stated above: 4′, 3a, 7″, 6c, 5‴, 2⁗, and 4s. It is generally assumed that the hypotheca is more conservative than the epitheca, and this is true of the present organism. Deviations from the normal epithecal plate configuration were observed in about 10 per cent of the specimens examined. The range of variation encountered in the atypical specimens of *S. sweeneyi* was rather exceptional for dinoflagellates, although similar variations occur in *Pyrophacus horologicum.* Plate formulae in these atypical specimens were:

(1) 4′, 2a, 6″;
(2) 4′, 3a, 5″;
(3) 4′, 3a, 4″;

A single specimen with 3′, 3a and 5″ showed an exceptional overgrowth of 1″, which reached the apical pore thus transforming 2′ into 1*a*.

No alteration of hypothecal formula has been noticed in actively growing cultures. In old cultures, I have observed hypothecal formulae of: 5‴, 2⁗ and one intercalary; 4‴, 2⁗; and 3‴, 2⁗ and one intercalary. However, the plate variation of the hypotheca has not exceeded two per cent in all examined specimens.

Discussion. The general characteristics of this organism place it in the *Peridiniaceae.* If it were classified solely on the basis of its major body plates, it would be included in the genus *Peridinium.* The cingular formula and sulcus plates are characteristically different, however, from those of *Peridinium.* The cingular and sulcal plates are conservative and important structural features connected with the most dynamic parts of the cell. Undoubtedly this organism belongs to a new genus. The species is also new. The only other known species which bear general resemblances to the present organism are *Peridinium subsalsum* Ost., and especially *P. trochoideum* (Stein) Lemm. Laboratory cultures of these species were provided by Dr. Sweeney for comparative studies. Their assignment to the genus *Peridinium* was clearly correct, but they bore only superficial resemblances to *Scrippsiella sweeneyi.* The genus is named after the institution at which it was discovered, and the species is dedicated to Dr. Beatrice M. Sweeney who made the original isolation and whose cultures made this study possible.

Fragilidium heterolobum n. gen. n. sp.

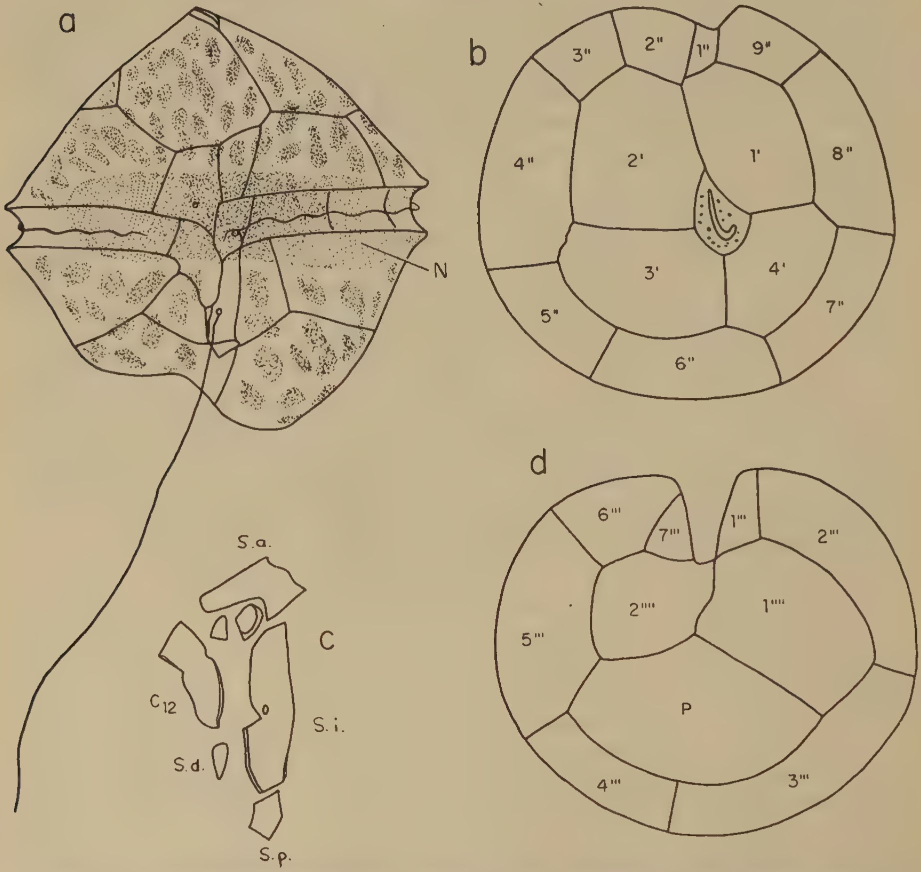

FIGURE 3. *Fragilidium heterolobum.* a) A typical individual, ventral view. b) Apical view of the epitheca. c) Sulcal plates. d) Antapical view of the hypotheca. All figures about × 1000.

Diagnosis. Medium-sized, roughly roundish pentagonal in ventral view. Epitheca dome-shaped; hypotheca asymmetrically bipedal, the left lobe being the largest. Cingulum deeply impressed, subcentral, descending, displaced distally about one girdle width, without lists. The cingulum has eleven sub-equal rectangular plates plus a transitional plate at the right end. Sulcus narrow, only slightly excavated, with six plates. Theca easily exuviated. Cell length 53–56 μ, transdiameter 48–54 μ. Chromoplasts numerous, elliptical, brown. Genus characterized by the high number of precingular, postcingular and cingular plates. La Jolla, California.

Description

Plate pattern. The epithecal formula is 4′, 9″ and a "pore platelet." The plate 1′ is in general large and it has the most irregular form. It has connections with seven plates: 1″, 2″, the pore platelet, 4′, 8″ and 9″; its border for 2″ is the smallest. Plate 1′ is asymmetrically located, most of it being on the right side of the epitheca; its width decreases gradually to the left. The other three apicals are more regular. Apical 2′ has six edges (for 1′, 3′, the pore platelet, 2″, 3″, 4″). The plate 3′ touches 2′, 4′, 4″, 5″, 6″ and the pore platelet. The apical 4′ touches 3′, 1′, 6″, 7″, 8″ and the pore platelet.

The so-called pore platelet is relatively large, oval sigmoid, and placed obliquely to the median plane, *i.e.*, the plane which passes through the sulcus, the joint of 1″ and 9″, and the apex. This plate is variable but generally it has a convex left side subdivided into two edges for 2′ and 3′, a concave side which touches 1′, a major pole for 4′, and a minor one for the suture between 1′ and 2′. The most characteristic feature of this plate is a long and narrow reinforcement at the middle of the plate, sigmoid, with a dorsal hook to the right; it is variable sometimes double. Along it there are sometimes a few very small pores.

The most characteristic precingulars are 1″ and 9″. The first, trapezoidal in shape, is the smallest. The precingular 9″, pentagonal, has two edges at the left: the superior one for 1′ and the posterior, reinforced, forms a part of the right border of the sulcus. The precingulars 3″, 5″, and 7″ are more or less quadrangular.

The hypothecal formula is 7‴, 2⁗ and 1p. The narrowest postcingular plates are 1‴ and 7‴. The latter is the smaller and is somewhat displaced posteriorly. The antapicals are very asymmetrical, the left one being much longer. The suture between 1⁗ and 2⁗ is irregular. Antapical 2⁗ contacts the sulcus more than 1⁗, which just barely touches it. The intercalary (p) is a large irregular plate, bordered by the antapicals, 3‴, 4‴ and 5‴.

All plates of the epi- and hypotheca are smooth. Some spots of different optical densities could be seen in a few specimens, especially in plate 1″, with oil immersion and phase contrast. There are sometimes pores located on the cingular border of this plate.

The cingulum is formed by eleven subequal retangular plates, plus another different plate at its right end. This C_{12} is curved, irregular, extending somewhat into the sulcus, with a narrow left-posterior or sulcal end. For that reason this plate could be named "transitional." The cingular plates lack sculptures.

The sulcus is narrow, has six plates, and is only slightly excavated. The anterior sulcal plate has a very characteristic "boomerang" shape, with a posterior concavity and a longer and narrower right arm. In its sinus there are two very tiny platelets; the right one is the smaller. Behind the anterior plate and in contact with 1‴ there is a long plate, with a little sinus at the middle of its right border, where C_{12} ends. In connection with the latter, there is another small plate. Finally, there is a posterior sulcal plate.

Protoplasm. The protoplasm is surrounded by a strong membrane and contains more than one hundred elongate-elliptical chromatophores which are dark yellowish-brown. Food is stored as numerous granules of variable shape, which are generally small and located most abundantly in the peripheral layer.

The nucleus is large and compact, and is surrounded by a strong membrane. It is elongated in the equatorial plane, is somewhat curved, and has very dense thin threads of granular chromatin more or less perpendicular to the major axis of the nucleus. At the concavity, I sometimes observed large masses that were not distinctly granular.

The longitudinal flagellum extends beyond the antapex about two and a half cell lengths; it has a fast vibratory movement of short amplitude. The transverse flagellum, very slightly flattened, is long and completely encircles the girdle. The organism swims with a predominantly rotating motion.

Dimensions (in fixed and slightly distorted cells). Length 53–56 μ; transdiameter 48–54 μ. In an individual with a length of 55.5 μ, the epitheca was 27.5 μ and the hypotheca was 24 μ in length.

Variations. I have observed some variation in form (cell length more or less short in comparison with the transdiameter) and also in the plate pattern. Sometimes 4″ appears divided into two plates; thus the postcingular series sometimes has eight instead of seven plates. Occasionally there are eight instead of nine precingulars, and in one individual, a very narrow 1′ was observed fused with the pore platelet.

The normal formula is: 4′, 9″, a pore platelet, 12c, 7‴, 2⁗, 1p and 6s.

Discussion

The only difficulty encountered in the tabulation of this organism was the rapidity with which it exuviated its plates. Most of the individuals were found in a quiet state, short ellipsoidal in form, and without theca. The actively swimming cells were of course difficult to measure and draw. Any attempt to stop them for a moment led to cell deformation and ecdysis. This is accomplished in a very peculiar way: all the plates separate from each other, but in general, they remain surrounding the cell at a short distance, forming a regular assemblage. The plates are very delicate.

The plate pattern of this species is fundamentally different from all of those previously known (Balech, 1956; Biecheler, 1952; Dangeard, 1927; Graham, 1942; Kofoid, 1907–33; Lindemann, 1928; Schiller, 1933, 1937). The differences are in both the epi- and hypotheca. Since very little is known regarding the cingulum and sulcus of most dinoflagellates, we cannot discuss the differences concerning these regions. Nevertheless, it should be pointed out that the structure of the sulcus of this species is different from that of all sulci already studied, and no other genus is known with such a high number of girdle plates.

Other genera without epithecal intercalaries and with four apical plates are *Diplopsalis, Dolichodinium, Goniodinium, Glenodinium, Cladopyxis,* and *Ceratium.* The two latter are very different in form, bearing strong horns or arms, and with many differences in plate pattern. *Diplopsalis* as defined by Lindemann (1928) is actually an assemblage of several genera. But even on these terms, *Diplopsalis* never has more than seven precingulars, five postcingulars and it lacks the posterior intercalary. *Glenodinium,* as defined by Schiller (1933–37), is another very heterogeneous assemblage with a very large variation of plate patterns. None of its species has so many pre- and postcingular plates, and they also lack posterior intercalaries. *Dolichodinium* seems to have only six girdle plates and has six precingulars and six postcingulars instead of nine and seven. *Goniodinium* is perhaps the genus most closely related to *Fragilidium,* but it has only six precingulars and six postcingulars; instead of one posterior intercalary it has three intercalaries in the hypotheca. Until the discovery of *Fragilidium, Goniodinium* was the genus with the highest known number (nine) of cingular plates (this number, however, was not stated with certainty).

The high number of precingular, postcingular and cingular plates is sufficient to characterize this new genus. The only other genera with seven postcingulars are *Glenodiniopsis* and *Heterodinium*. *Pyrophacus* is the only genus with a higher number of these plates.

Fragilidium heterolobum was isolated from plankton at La Jolla (San Diego, California) on March 20, 1957.

SUMMARY

1. Two new genera and species of dinoflagellates are described. Both were originally isolated from plankton samples collected at La Jolla (San Diego, California).

2. *Scrippsiella sweeneyi* is a small species with the general tabulation of an *Orthoperidinium,* but it differs in having six cingular plates. The structure of the sulcus is also different. A great deal of variation in plate pattern was exhibited by this organism.

3. *Fragilidium heterolobum* is a medium-sized species having a tabulation that is quite different from all previously described dinoflagellates. It has a very high number of cingular plates (twelve). The generic name refers to the characteristic frequency and suddenness with which it sheds its plates.

LITERATURE CITED

Balech, E., 1956. Etude des Dinoflagellés du sable de Roscoff. *Revue Algologique Nlle.,* Serie 2(1–2): 29–52.

Biecheler, B., 1952. Recherches sur les *Peridiniens. Supp. au Bull. Biologique de France et de Belgique,* **36**: 1–149.

Dangeard, P., 1927. Phytoplankton de la croisière du Sylvana. *Ann. Inst. Oceanog.,* **4** (8): 285–407.

Graham, H. W., 1942. Studies in the Morphology, Taxonomy and Ecology of the *Peridiniales.* Scientific results of Cruise VII of the Carnegie during 1928–29. Carnegie Inst. of Washington Publication 542.

Kofoid, C. A., 1907. New species of dinoflagellates. *Bull. Mus. Comp. Zool. Harvard,* **50**: 163–207.

Kofoid, C. A., 1911. Dinoflagellata of the San Diego region. V. On *Spiraulax,* a new genus of the *Peridineae. Univ. Calif. Pub. Zool.,* **8**: 295–300.

Kofoid, C. A., and A. M. Adamson, 1933. The *Dinoflagellata:* the family *Heterodiniidae* of the *Peridinioidiae. Mem. Mus. Comp. Zool. Harvard,* **54** (1), 136 pp.

Kofoid, C. A., and J. R. Michener, 1911. New genera and species of Dinoflagellates. *Bull. Mus. Comp. Zool. Harvard,* **54**: 265–302.

Lindemann, E., 1928. *Peridiniales. In:* Engler and Prantl, Die Pflanzenfamilien. 2nd Ed., Vol. 2, 104 pp.

Shiller, J., 1933, 1937. *Dinoflagellatae (Peridineae). In:* L. Rabenhorst's Kryptogamenflora. Vol. 10, Leipzig.

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Aggregates of Bacteria in Sea Water as Determined By Treatment With Surface Active Agents[1]

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ABSTRACT

Sea water samples were treated with the surface active agents, Tween 80, MYRJ-52, Renex 31, and Dow Corning Antifoam AF Emulsion to determine their effect on the dispersal of microbes in aggregates. All of these substances in the concentration of 10 ppm increased the plate counts compared to untreated controls. In the case of Tween 80, the most carefully studied of the wetting agents, the results from different water samples were somewhat variable, with an average of almost twice as many colonies developing from the treated sea waters. Mechanical agitation of the sea water had little effect on the number of colonies developing on plates compared to stationary controls. Maximum development of colonies on agar pour plates occurred when sea water samples were treated with 1 to 10 ppm Tween 80. There was evidence for inhibition of pigmented colonies at concentrations of the wetting agent higher than 10 ppm as indicated by serial dilution and replica plate methods.

Direct microscopic observations of microorganisms from water before and after treatment with the surface active agents indicated the occurrence of cells in large clumps, usually on detritus, and individual cells. Less than 13 per cent of the total number of cells was removed from the aggregates by the surface active substances. There was a tendency for the percentage of clumped bacteria to be inversely proportional to the total microscopic count.

The dispersal of bacterial clumps by the surface active agents is attributed to their surface tension depression.

INTRODUCTION

The existence of the microbial flora of aquatic environments in clumps has been suggested by various investigators (Lloyd 1930, Benecke 1933, ZoBell 1946). Such associations may have important ecological implications such as the interchange of metabolites, reduction of exoenzyme escape, and concentration of nutrients. Aggregates of microorganisms complicate cultural methods of enumeration (Butterfield 1933, Jannasch and Jones 1959).

In the present investigation, the effect of surface active agents on the dispersal of aggregated microbial cells in sea water has been studied by colony enumeration and direct microscopic observation. The influence of different concentrations of the surface active agent, Tween 80, on the development of marine microorganisms has been considered.

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METHODS

Sea water samples were collected aseptically, and 99 ml were dispensed into sterile glass containers (6-oz screw-cap prescription bottles or 250-ml Erlenmeyer flasks). Small amounts of surface active agents were added to one set of vessels, while others were left untreated as controls.

The effect of mechanical agitation on the dispersal of aggregates was tested by shaking a group of samples on a gyrotory shaking machine describing a circle about ¾″ in diameter.

After treatment, aliquots of the sea water samples were transferred to sterile 100-mm

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glass petri plates. Agar pour plates were prepared from one of the following media:

Ingredients	2216E g/L	Glucose g/L	2216E + g (glucose) g/L
Bacto-peptone	5.0	—	5.0
Bacto-yeast extract	1.0	—	1.0
Glucose	—	10.0	10.0
NH_4NO_3	—	1.0	—
K_2HPO_4	—	0.1	—
$FePO_4$	0.01	—	0.01
Bacto-agar	15.0	15.0	15.0
Aged sea water, one liter, salinity adjusted to 28 ± 0.5 g/L for all media.			
pH	7.6–7.8	7.6–7.8	7.6–7.8

The replica plate technique of Lederberg and Lederberg (1952) was used for determining the toxicity of Tween 80 on a population of marine bacteria.

Aggregates of bacteria in sea water were observed before and after treatment with surface active agents by the direct microscopic method of Cholodny as modified by Jannasch and Jones (1959). This technique involves microscopic enumeration of bacteria on glass slides after concentration by filtration through a membrane filter. Ten microscopic preparations were made of each concentrate, and 25 to 45 fields were counted depending on the amount and distribution of solid particles on the slides.

The surface active agents employed in this investigation were Tween 80, MYRJ-52, and Renex 31 from the Atlas Powder Company, Wilmington, Delaware. Tween 80 is a polyoxyethylene sorbitan monooleate. MYRJ-52 is a polyoxyethylene stearate. Renex 31 is an ether formed by the reaction of ethylene oxide with a highly branched chain synthetic aliphatic alcohol. Renex 31 has a high cloud point which makes it particularly applicable for sea water. All of these surfactants are nonionic emulsifiers. Dow Corning Antifoam AF Emulsion, a dimethyl polysiloxane fluid containing a few per cent of finely divided silica and conventional emulsifiers, was investigated.

In the tables, per cent error is calculated by $S\bar{x}/\bar{x} \cdot 100$, where $\bar{x}$ is the mean and $S\bar{x}$ is the standard deviation of the mean.

RESULTS

Effect of Tween 80 on plate counts. Sea water samples collected off the Scripps pier were shaken manually for two minutes with and without the surface active agent, Tween 80. The results are summarized in Table 1. The ratio of colonies developing from treated and untreated water varied from 0.95 to 3.2 with an average of 1.8 times more colonies developing on the plates from which the inoculum had been shaken with 10 ppm Tween 80.

Comparison of Tween 80 and AF Emulsion. Sea water samples were obtained off the Scripps pier. They were divided into three groups for treatment expressed as final concentrations: no additions, 10 ppm Tween 80, and 10 ppm AF Emulsion. One set of water samples thus treated was placed on the gyrotory shaking machine for 15 minutes at approximately 260 rpm. The other set remained stationary as a control. In order to determine the effect of 10 ppm Tween 80 on the nutrition of marine microorganisms, a final concentration of 10 ppm Tween 80 was incorporated into one batch of 2216E agar, and the samples were plated in five replicates with 2216E agar and 2216E + Tween 80 agar.

Tween 80 dispersed microbial clumps more efficiently than the AF Emulsion (Table 2). Both surface active substances produced increased plate counts compared to untreated water. The effect is ascribed, mainly, to the influence of the lowered surface tension produced by the surface active materials on microbial aggregates in sea water. The dimethyl polysiloxane polymer is reported to have little effect on the growth of biological materials (personal communica-

TABLE 1. *Effect of 10 ppm Tween 80 on the plate counts of sea water collected off Scripps pier*

Duplicate plates were incubated at 25 ± 1°C for 5 days.

Medium	Number of samples	Ratio of plate counts: treated with Tween 80/no treatment	Per cent error
2216E	6	1.62	13.7
Glucose	6	2.22	13.5
2216E + Glucose	3	1.47	7.4

(304)

TABLE 2. *Effect of 10 ppm Tween 80 and 10 ppm AF Emulsion on the plate counts of sea water collected off the Scripps pier*

Five replicates of treatments plated with 2216E and 2216E + 10 ppm Tween media and incubated at 25 ± 1°C for five days.

	No treatment		AF Emulsion		Tween 80	
	Shaken	Stationary	Shaken	Stationary	Shaken	Stationary
2216E Medium						
Microorganisms/ml	680	630	710	740	1,040	1,330
Per cent error	3.3	12.1	12.0	11.5	13.3	14.1
Ratio—treated/no treatment			1.05	1.17	1.54	2.10
2216E + 10 ppm Tween 80 Medium						
Microorganisms/ml	508	700	750	870	820	1,510
Per cent error	12.3	8.3	7.1	6.7	5.5	10.7
Ratio—treated/no treatment			1.16	1.21	1.47	2.16

TABLE 3. *Effect of various surface active agents on the plate counts of sea water collected off Scripps pier and a local tide pool*

Quadruplicate 2216E plates were incubated at 18 ± 1°C for 5 and 22 days.

	No treatment		Tween 80 1 ppm		Tween 80 10 ppm		Renex 31 10 ppm		MYRJ-52 10 ppm	
	5 days	22 days	5 days	22 days	5 days	22 days	5 days	22 days	5 days	22 days
Scripps pier water										
Microorganisms/ml	25	71	54	97	56	103	60	105	41	89
Per cent error	12.0	4.2	14.8	9.8	11.6	13.6	7.5	4.3	11.0	5.1
Ratio—treated/no treatment			2.16	1.37	2.24	1.45	2.40	1.48	1.64	1.25
Tide pool water										
Microorganisms/ml	75	107	97	166	113	171	136	200	196	223
Per cent error	8.7	7.0	11.9	11.1	14.6	12.6	6.6	12.8	5.9	6.5
Ratio—treated/no treatment			1.29	1.55	1.51	1.60	1.81	1.87	2.61	2.08

tion from the Dow Corning Corporation), and 10 ppm Tween 80 added to 2216E agar did not change the colony counts significantly in either direction compared to 2216E agar alone.

The surface active agents were no less effective in dispersing bacterial aggregates under stationary conditions than where the sea water samples were agitated. This result indicates that moderate mechanical agitation has little effect on breaking up clumps.

Comparison of Renex 31 and MYRJ-52 with Tween 80. Renex 31 and MYRJ-52 were compared with Tween 80 for their ability to disperse bacterial clumps in sea water. All of these wetting agents were used in concentrations of 10 ppm,. and Tween 80 was used in a concentration of 1 ppm as well. Sea water samples were procured off the Scripps pier and from a local tide pool. Each of the experimental samples was shaken on the gyrotory shaking machine for 30 minutes at approximately 260 rpm and plated in quadruplicate. The plates were incubated at 18 ± 1°C for 5 and 22 days.

In all cases, treatment of sea water with the surface active agents increased the number of colonies developing on agar plates (Table 3). Renex 31 and MYRJ-52 appear to be as effective as Tween 80 in dispersing microbial clumps in sea water. There was little difference in the effectiveness of 1 or 10 ppm Tween 80.

Effect of different concentrations of Tween 80. The problem of the toxicity of the surface active agents and the concentration

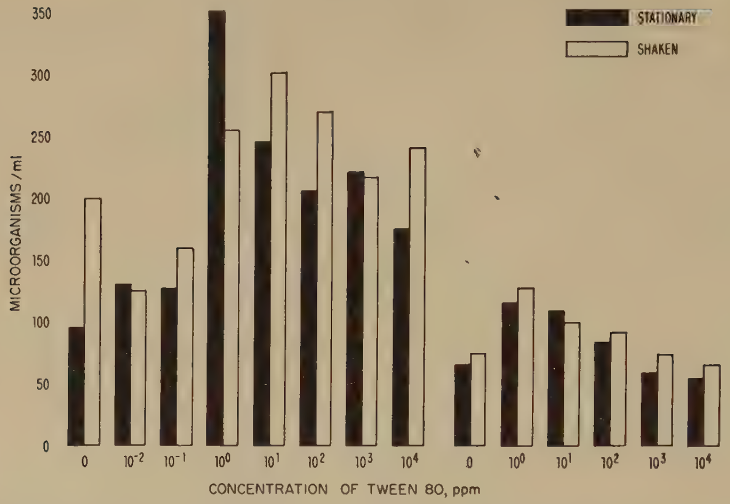


FIG. 1. The effect of different concentrations of Tween 80 in two separate experiments on the number of microbial colonies developing on 2216E agar plates. Quadruplicate plates were incubated at 25 ± 1°C for five days.

where the substances were most effective for dispersing aggregates was investigated. Surface sea water from off the Scripps pier was treated with concentrations of Tween 80 ranging from 10^{-2} to 10^4 ppm increasing by increments of the power 10. In two experiments one set of 250-ml Erlenmeyer flasks was shaken for 30 minutes at approximately 190 rpm on the gyrotory shaking machine while another set of flasks remained stationary.

The data in Figure 1 indicate that the optimum concentration of Tween 80 for maximum cell dispersion and minimum toxicity is 1 ppm. However, 10 ppm Tween 80 produces a considerably greater drop in surface tension, 4 and 20 dynes per cm depressions for 1 and 10 ppm Tween 80, respectively.

As indicated in Figure 1, there was no consistent difference between the number of colonies developing from water samples that were shaken or stationary. There was a noticable difference between the types of colonies developing on the agar plates from sea water samples treated with different concentrations of Tween 80. The kinds of colonies progressively decreased in abundance as the concentration of Tween 80 increased as judged by their chromogenic properties, colony characteristics, and cell morphology. At concentrations of 10^3 and 10^4 ppm Tween 80 almost all of the colonies were colorless, smooth forms. These results suggest that Tween 80 in high concentration is toxic for many marine microorganisms and that resistant forms are greatly dispersed.

In order to obtain more information on the relative toxicity of Tween 80, the development of various heterogeneous populations of marine microorganisms as colonies on 2216E agar plates were tested on the same medium plus Tween 80 in concentration of 10^0 to 10^4 ppm at increments of the power 10. The pattern of microbial growth was transferred from the initial agar plates to the sterile Tween 80 series by the replica plate method. The plates were allowed to set for 24 to 48 hours prior to inoculation to check sterility and remove excess moisture. For each test, five different 2216E agar plates harboring a diversity of aerobic heterotrophic marine colonies were selected and replicated on the Tween 80 plates in descending order of concentration. The number of colonies developing on the various concentrations of Tween 80 is expressed as per cent of untreated control colonies in Table 4. The surface tensions of aged sea water containing Tween 80 were determined with a Du Noüy tensiometer (Table 4).

A progressive toxicity for Tween 80 was

TABLE 4. *Effect of different concentrations of Tween 80 on a population of marine microorganisms determined by the replica plate method of Lederberg and Lederberg (1952)*

Five replicate 2216E plates were incubated at 25 ± 1°C for 5 days.

Concentration of Tween 80 in ppm	Surface tension (dynes/cm)	Mean % survival of replicated colonies	Per cent error
0	73	100	—
10^0	69	92	1.2
10^1	52	75	1.8
10^2	44	67	1.9
10^3	43	61	1.8
10^4	42	55	2.3

expressed by development of colonies on the plates using the replica plate technique. Where microbial colonies from other water masses were tested by this method, the relative per cent counts were not suppressed to the same extent as those reported in Table 4. However, 10 to 15 per cent inhibition was the minimum observed at the higher concentrations of the surface active agent. A selection for nonchromogenic, mucoid colonies at the higher concentrations of Tween 80 was noticed as before.

Direct microscopic evidence of microbial clumps in sea water. Various kinds of associations between solid material and attached bacterial cells were observed using the Cholodny method. Errors in distinguishing between free and aggregated bacteria may occur if the density of detritus particles is too high in the microscopic preparations. Consequently, the amount of water treated was determined by its content of living and dead particulate matter.

In neritic waters particles were covered or closely surrounded by microorganisms (Fig. 2 and 3). Attachment of bacteria to apparently dead diatoms was observed in the same environment (Fig. 4). Short chains of bacterial cells also are considered as bacterial aggregates (Fig. 5). Clumps such as that shown in Figure 6 were typical for depths of 100 and 200 meters in oceanic areas. Filamentous and twisted forms were observed with apparent spore-forming rods next to amorphous matter. Spirilli-like forms are common, but they have never been observed in clumps (Jannasch and Jones 1959).

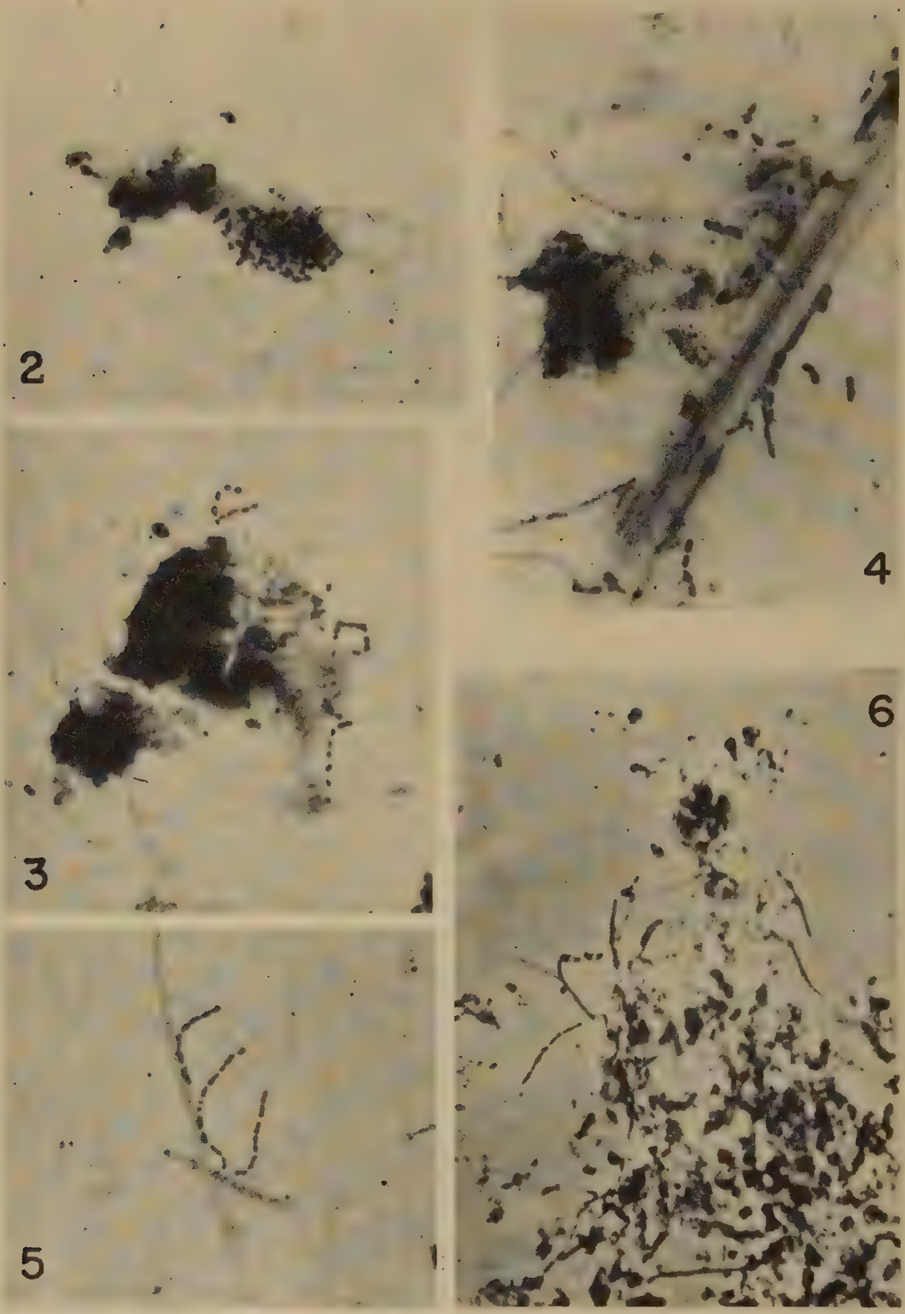
The numbers of bacteria observed microscopically in the two samples reported in Table 3 and five other samples obtained from a vertical cast on the open sea are presented in Table 5. The third and fourth columns of Table 5 present the percentage of bacteria found in aggregates before and after treatment with Tween 80. It was possible to distinguish individual cells even in aggregation as demonstrated in the photomicrographs. The percentage of dispersal of clumps by treatment with Tween 80 was low, particularly in samples containing large numbers of cells. Even so, the estimated total number of microorganisms released from clumps is apparently much larger than the increase of the cell count recorded by the agar pour plate method. In the pier sample (Tables 3 and 5), for example, a 4.4 per cent decrease in the number of clumped organisms resulting from treatment with Tween 80 as determined microscopically corresponded to the dispersal of about 2,500 individual cells compared to a 145 per cent increase in the number of free cells or about 30 colonies by the plate method. Explanations for the considerable differences recorded from the methods have been discussed by Jannasch and Jones (1959).

In contrast to the results obtained microscopically from neritic waters were those of a vertical cast in an oceanic area (Table 5). There was a tendency for the percentange of clumped microorganisms to be lower when

TABLE 5. *Clumped and individual bacteria as observed microscopically before and after treatment with 10 ppm Tween 80*

Location	Total number of bacteria	Per cent clumped bacteria: Before treatment	Per cent clumped bacteria: After treatment	Drop in percentage of clumped bacteria
Scripps pier	55,400	26.3	21.9	4.4
Tide pool	46,100	14.7	12.0	2.7
Vertical cast:*				
Surface	24,400	20.2	14.2	6.0
25 m	6,200	41.1	22.5	18.6
50 m	4,300	36.7	23.9	12.2
75 m	7,900	58.4	32.0	26.4
100 m	9,700	29.6	3.8	25.8
200 m	9,100	13.9	6.0	7.9

* At 32° 38′ N latitude; 117° 32′ W longitude.



Microscopic preparations obtained by the Cholodny method, stained with a 1 per cent solution of erythrosine in 5 per cent phenol, and photographed using a blue filter. Fig. 2. Scripps pier sample, magnification 1,000×. Fig. 3. Tide pool sample, magnification, 1,000×. Fig. 4. Scripps pier sample, magnification 750×. Fig. 5. Scripps pier sample, magnification 1,200×. Fig. 6. From 200 meters at 32° 38′ N latitude; 117° 32′ W longitude, magnification 1,000×.

the total counts were higher. More individual cells were dispersed from aggregates in the samples obtained from depths of 25 to 100 meters than from the surface or from neritic areas. At 200 meters, however, few clumps were observed. There was a high percentage of individual filamentous forms. No comparative values with the plate method are recorded due to the very low plate counts obtained at sea.

DISCUSSION

With the exception of Tween 80, little is known about the effect of the surface active substances on bacterial development. The influence of surface active agents on bacterial metabolism involves charge, structure, and concentration (Hotchkiss 1946, Glassman 1948). Tween 80, in addition to the other surfactants employed, is a non-ionic wetting agent, and there is no way to relate the charge of these compounds to their activity.

Although Ivarson and Pramer (1956) have shown that 25 and 250 ppm Tween 80 had no significant effect on the total number of bacteria obtained by plate counts from a 1/10 dilution of soil, the present results indicate approximately twice as many bacterial colonies obtained by plate counts upon shaking with 1 and 10 ppm Tween 80 in sea water. Explanations for these differences may reside in the lower nutrient concentrations of sea water, which may tend to promote clumping (ZoBell 1946), and the possibility of toxicity from the higher concentrations of Tween 80 employed by Ivarson and Pramer.

The toxicity of Tween 80, especially at high concentrations, was noted during this investigation. Davis and Dubos (1946) showed that small inocula of tubercle bacilli were inhibited by small amounts of unesterified oleic acid present in Tween 80. It is possible that the toxicity of Tween 80 at higher concentrations in these experiments was due to traces of unesterified oleic acid. Tween 80 in concentrations of 1000 ppm has been employed to induce submerged and diffuse growth of the tubercle bacilli (Dubos and Davis 1946). The surface active properties of Tween 80 are considered more important for stimulating submerged growth of mycobacteria in liquid media than the chemical structure, since nonsurface active oleic acid esters are not effective.

Concentrations of 3,000 to 20,000 ppm Tween 80 caused *Staphylococcus aureus* to grow as a smooth variant in broth but did not affect the colony structure on agar (Gershenfeld and Johnson 1953). Concentrations of 50 and 250 ppm Tween 80 had no inhibitory effect on the development of *Thiobacillus thiooxidans* (Starkey *et al.* 1956). MacLeod *et al.* (1958) tested a variety of surface active compounds for their nutritional effect on a marine *Flavobacterium*. The growth promoting properties of the surface active compounds were attributed to their surface active properties rather than to any capacity to serve either as precursors of cellular lipids or as sources of fatty acids. However, Williams *et al.* (1947) implicated Tween 80 in the metabolism of *Lactobacillus bulgaricus* as a non-toxic source of oleic acid which was essential for growth if biotin was omitted.

In this investigation, the effect of the surface active agents is considered to be primarily physical since the concentrations of the wetting agents were lower than those used by most other investigators. The microbial populations in the sea water were exposed to the surface active substances for only a relatively short period of time before plating with nutrient agar devoid of surfactants. In the experiment where 10 ppm Tween 80 was incorporated into the agar medium, no difference was observed between the colonies on these plates and those containing no Tween 80. However, where the samples were treated with higher concentrations of Tween 80 (10^3 to 10^4 ppm), there was apparent selection in the type of colonies developing. While we are aware of the metabolic effect of many surface active substances, the increase in colony counts resulting from treatment of sea water with the surface active substances in this study is ascribed to the dispersal of portions of microbial aggregates.

REFERENCES

Benecke, W. 1933. Bakteriologie des Meeres. Abderhalden's Handb. biol. Arbeitmethoden, IX Abt., T. 5: 717–854.

Butterfield, C. T. 1933. Comparison of the enumeration of bacteria by means of solid and liquid media. Public Health Repts., **48:** 1292–1297.

Davis, B. D., and R. J. Dubos. 1946. Interaction of serum albumin, free and esterified oleic acid and lipase in relation to cultivation of the tubercle bacillus. Arch. Biochem., **11:** 201–203.

Dubos, R. J., and B. D. Davis. 1946. Factors affecting the growth of tubercle bacilli in liquid media. J. Exptl. Med., **83:** 409–423.

Gershenfeld, L., and G. C. Johnson. 1953. Effect of certain surface active agents upon bacterial growth. J. Amer. Pharm. Assoc., **42:** 187–192.

Glassman, H. N. 1948. Surface active agents and their application in bacteriology. Bacteriol. Rev., **12:** 105–148.

Hotchkiss, R. D. 1946. The nature of the bactericidal action of surface active agents. Ann. N. Y. Acad. Sci., **46:** 479–494.

Ivarson, K. C., and D. Pramer. 1956. The persistence and biological effects of surface active agents in soil. Soil Sci. Soc. Amer. Proc., **20:** 371–374.

Jannasch, H. W., and G. E. Jones. 1959. Bacterial populations in sea water as determined by different methods of enumeration. Limnol. Oceanogr., **4:** 128–139.

Lederberg, J., and E. M. Lederberg. 1952. Replica plating and indirect selection of bacterial mutants. J. Bacteriol., **63:** 399–406.

Lloyd, B. 1930. Bacteria in the Clyde Sea area: a quantitative investigation. J. Mar. Biol. Ass. U. K., **16:** 879–908.

MacLeod, R. A., H. Hogenkamp, and E. Onofrey. 1958. Nutrition and metabolism of marine bacteria. VII. Growth response of a marine *Flavobacterium* to surface active agents and nucleotides. J. Bacteriol., **75:** 460–466.

Starkey, R. L., G. E. Jones, and L. R. Frederick. 1956. Effects of medium agitation and wetting agents on oxidation of sulfur by *Thiobacillus thiooxidans*. J. Gen. Microbiol., **15:** 329–334.

Williams, W. L., H. P. Broquist, and E. E. Snell. 1947. Oleic acid and related compounds as growth factors for lactic acid bacteria. J. Biol. Chem., **170:** 619–630.

ZoBell, C. E. 1946. Marine microbiology: a monograph on hydrobacteriology. Chronica Botanica, Waltham, Mass. 1–240 pp.

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CURRENT PROBLEMS IN RESEARCH

Marine Sediments

Recent sediments give important clues about conditions under which sedimentary rocks may have been formed.

Francis P. Shepard

Most sedimentary rocks are believed to have been deposited in the seas of the past. One of the primary purposes in geological investigations has been to interpret the conditions under which these ancient sediments were deposited. One of the obvious places to look for guidance in these interpretations is in the deposits of the present. It is, therefore, rather surprising to find how little attention geologists had paid to these recent marine sediments until very recent years. Up until World War II only a few individuals were interested in remedying the situation (*1*). Even the large-scale oceanographic investigations, which were initiated shortly before the war, had helped little in the interpretation of ancient sediments because they had been largely concerned with the deep-ocean floor, and most marine sedimentary rocks now on the continents were probably deposited in relatively shallow seas.

For many years some of the leaders in petroleum geological research had recognized the importance of carrying on investigations of the sediments of today, and finally, in 1950, they developed a project supported by the American Petroleum Institute which had as its aim the study of near-shore marine deposits as an aid in the interpretation of ancient sediments. To date, the field work of this project, which we have administered at the Scripps Institution of Oceanography, has been confined to the northwestern Gulf of Mexico (*2*), although plans are now under way to continue the studies in the Gulf of California. Meantime, a number of other projects, largely supported by petroleum companies, have been carried on elsewhere. Notable among these have been the studies of the Bataafsche Petroleum Maatschappii, of the Hague, around the Orinoco Delta, Trinidad, and the Gulf of Paria (*3*); of the U.S. Geological Survey among the coral reefs of the western Pacific Ocean (*4*); of the Hancock Foundation off the southern California coast (*5*); of the Soviet Union in the various seas that surround the U.S.S.R. (*6*); and of the Germans, especially in the Baltic (*7*).

As a result of these studies of recent sediments it is now easier to interpret

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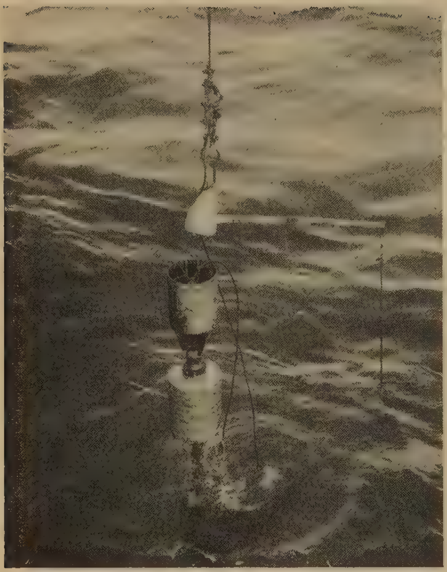

Fig. 1. A piston corer, modified from the Kullenberg type. A weight attached to the arm extends below the pipe and releases the core barrel and weights when it reaches bottom. The loop of wire allows the core barrel to fall free after release.

the environments in which many sedimentary rocks were deposited. The petroleum companies are making good use of this information in their search for oil.

Instruments

The instruments used in obtaining samples of recent sediments are for the most part quite simple in principle, in contrast to the amazing devices of the nuclear and space age. Cores of the ocean bottom are obtained partly by lowering heavily weighted pipes to the bottom and bringing up the core obtained when the pipe sticks into the soft sediments. A more complicated but much more successful method was devised by Börje Kullenberg (*8*), who placed a piston inside the pipe, which he attached to the winch cable. The heavily weighted pipe is allowed to fall free over the piston after a trigger weight has hit bottom (Fig. 1). The piston greatly reduces the friction of the mud entering the core barrel, so that much longer cores are obtained, and there is much less loss of length than is found in ordinary cores, where the sediment is pushed aside by the coring operation.

Various types of instruments which grab samples from the bottom are used. One of the most successful is the Van Veen grab (*9*), which obtains a sample of about 2 cubic feet. Orange-peel buckets of slightly smaller size are also used, but these are not very successful except in shallow water, whereas the Van Veen has been used at the greatest depths. Other samplers are used in shallow water from a vessel that is under way. These are shaped like a torpedo; they descend nose first, take a bite of the bottom, and return with the nose upward. The sediment is also held in by a lid, which closes after the sampler hits the bottom.

One of the most interesting developments in marine geology has come from the use by geologists of the Aqualung, made famous by its inventor Jacques Cousteau. The scuba (*10*) divers, as they are called, carry with them geological hammers, compasses, inclinometers, and cameras. They work at depths down to about 300 feet, and much exploration of the sea floor has been accomplished in this way. The bathyscaphe, invented by Auguste Piccard, has also been used to obtain data, but from considerably greater depths. Cameras which can take repeated photographs when lowered to the bottom have begun to provide us with much valuable information from great depths (*11*) (Fig. 2).

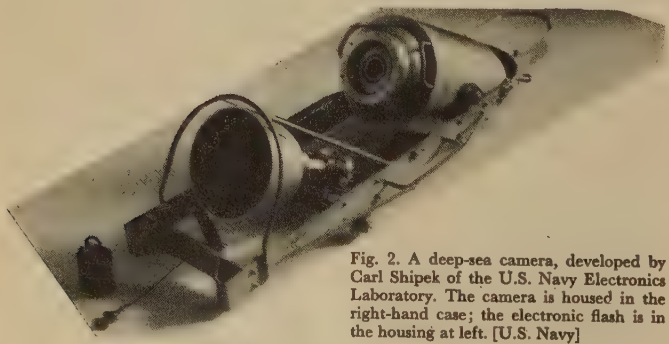

Fig. 2. A deep-sea camera, developed by Carl Shipek of the U.S. Navy Electronics Laboratory. The camera is housed in the right-hand case; the electronic flash is in the housing at left. [U.S. Navy]

Sandstones

In order to see how the characteristics of the recent sediments shed light on the conditions under which the sediments were deposited, let us consider some aspects of the origin of several of the most common types of rock.

Geologists usually define sandstones as rocks consisting of grains of detrital sediments which are predominantly within the size range of 1/16 millimeter to 2 millimeters in diameter. These rocks have been deposited either in the ocean or on the land, and many of them have been deposited along the border between the two, so they belong to some extent in each category. In general, sandstones are rather poor in fossils, and therefore the geologists need other criteria to interpret their origin.

Sheet sands. One common type of sandstone is characterized by its widespread continuity and is called a sheet sand. Some of these are formed by braided streams on a broad plain at the base of a mountain range. Although these fanlike deposits are well known to geologists, they are not easy to recognize in ancient rocks. Sheet sands containing marine fossils, and particularly those including forms of life characteristic of the open sea, have been even more difficult to interpret than the fans. Studies of the sea floor have shown that the continental shelves have many extensive areas of sand. The most puzzling thing about such sand areas is that the majority of them lie outside zones where the sediments are muddy—such as, for example, the broad sand belts along the outer continental shelf off the coasts of China. A similar outer-shelf sand has been studied off the Texas coast. The finding of shells that have been dated, by the carbon-14 method, as thousands of years old shows that, at least here, the sands may not have been deposited under present-day conditions. We know that the sea stood considerably lower during the ice ages, (because the water was locked up in glaciers), and it is believed that the rivers coming out onto this shelf carried more sand during glacial times than at present. As the sea rose, the rivers occupied estuaries and began depositing their sediments in these embayments, leaving many of the shelf sands uncovered. Furthermore, with the change in climate many rivers ceased transporting much sand to the sea and began introducing mud. This fine sediment could be deposited only where the currents of the sea floor were weak. Along many portions of the continental shelves the currents are strong enough to prevent mud deposition. These same currents move the sand back and forth on the outer shelf and may introduce the outer-shelf faunas into these former terrestrial or coastal sands.

Another type of marine sheet sand is found in shoal water where tides are very pronounced. Vast areas in the southern part of the North Sea are covered with sand which has been introduced in part from the English Channel by tides which run powerfully through the Straits of Dover. Another large area covered with sand occurs southeast of Cape Cod, in Nantucket Shoals, where the tides are constantly shifting the sand derived from the erosion of the cape. Farther to the east, on Georges Bank, there are equally extensive shoals. Here, much of the sand is remarkably pure quartz and well rounded, resembling the great glass-making sandstones of the Middle West, known as the St. Peter sandstone. Few fossils are found in the St. Peter sandstone, and a striking scarcity of shells characterizes the sands of Georges shoals. These, however, are only clues, and the two sands doubtless have quite different origins.

Shoestring sands. Other sandstones are characterized by their elongation and their lens shape in cross section. These sometimes form a reservoir in which oil accumulates, so their origin is a problem of much interest. Some of them show the characteristics of river sands, but others appear to be comparable to the great sand islands (Fig. 3) which form barriers along many of the lowland coasts of the world (*12*). By studying the characteristics of the recent sands in each of these environments, it is possible to identify the origin of many of the shoestring sandstones. Most of the sandy barrier islands have a straight or gently curving margin seaward and a scalloped margin facing the lagoon, whereas the river-channel sands have a slightly winding shape, with the two sides roughly parallel. In cross section the barrier islands are usually broader at the base than above but show asymmetry, whereas the river channel sands have a narrow concave base, are wider above, and have a rough bilateral symmetry.

The sediments are also quite different. The barrier sands are much better sorted, especially on the outside, where there are beaches and dunes. Some of the inner marshy flats developed by washovers from the ocean are somewhat muddy, especially where there are extensive ponds. The river sands are, in general, poorly sorted and have more lenses of gravel and of muddy sediments than the barriers. Unlike the sediment of the barriers, that in the river channels shows no contrast on the two sides. Studies of grain orientation show that in both cases the grains are elongated in the direction of flow (*13*). Therefore in the river channels the grains trend along the length of the channel whereas in the barrier islands, which receive their sediment from the outside, the grains are largely oriented across the sand body.

The faunas and floras are quite different. The river deposits contain an abundance of wood, which is rather scarce in the barriers. The ocean side of the barrier contains ocean shells, whereas the lagoon side has estuarine types. Shells are much scarcer in the river channels and consist largely of freshwater types.

Distinguishing between the beach and dune sands of ancient barrier-island deposits or of any coastal deposits has been somewhat difficult. Considerable study of the recent sands has provided some useful clues. Study of the type of bedding is often helpful, because the wind makes a special type of cross-bedding which is distinctive (*14*). When this cannot be found, other criteria are helpful. If the outcrops contain both dune and beach deposits side by side, the grains of the dune sands will almost always be more rounded (*15*) and the contrast will develop at the immediate point of contact, indicating that the wind has selected rounder grains, since there has not been enough transportation to produce rounding. The dunes almost always have more silt than the beach sands.

The idea long held by geologists that barrier islands are formed on coasts of emergence led to the thought that they were ephemeral features and, therefore, not likely to be preserved and to become reservoirs of oil. The work along the coast of the Gulf of Mexico, however, has shown that many or perhaps most of the barrier islands were built up by the waves as the sea level rose at the end of the glacial period, or after abandoned deltas sank beneath the sea. It seems likely that reexamination of shoestring sands will show that many of them are old barriers, as claimed many years ago by N. W. Bass (*12*).

Deep-sea sands. Geologists have long been puzzled by layers of coarse-grained sandstone interbedded with thick masses of shale, the former suggesting shallow-water conditions and the latter appearing to have been deposited in quiet deep water. They were at a loss to explain the sudden change of depositional conditions that was implied, particularly when it was found that the faunas of some of the shales were those representing deepwater conditions. These sandstones contain ripple marks and cross-bedding, both generally believed, in the past, to be a sure sign of shallow-water deposition. They even contain fragments of wood and shallow-water organisms. It was thought by some geologists that these sand and shale sequences indicated rapid, large-scale crustal movements so that deep-sea conditions alternate with those of shallow water or even of land.

The explanation of the phenomenon came when the Dutch geologist Kuenen (*16*) demonstrated with tank experiments that sand could be transported by currents resulting from a relatively heavy suspension of sediment and water. These currents can in turn be induced by slumping of the water-saturated sediments on a submarine slope, probably as the result of the development of spontaneous liquefaction (*17*). The extensive coring operations conducted by the Lamont Geological Observatory (*18*) did much to establish the great depth to which sand could be carried by this means. It can even be transported along a deep-ocean floor with little or no gradient. Almost all recent oceanographic cruises in various parts of the world have added to the record of these amazing currents. Many of them travel down submarine canyons, carrying the sands of the canyon head and the canyon walls out onto the deep fans which are found at the lower end.

The turbidity-current explanation for such sandstone layers has now been used widely, probably without enough caution in many cases. Actually there has been little study of the characteristics of deep-sea sands. Oceanographic institutions appear to have put too many of their resources into obtaining deep-sea cores and too little into studying the results. From preliminary investigations it has appeared that may of the deep-sea sands are graded—that is, the grains are coarse at the bottom and progressively finer above. This characteristic was also found in the experiments by Kuenen. Analyses of many of the deep-sea sands at Lamont and at Scripps, however, have shown that many of them are not perceptibly graded; others have alternating coarse and fine sediments in the same sand zone. Furthermore, graded bedding can be produced in several other ways, including the stirring up of sediment on the sea floor by great storm waves, so graded bedding by itself is not a safe criterion for assigning a turbidity-current origin to these sands (*19*).

Some study of the constituents of deep-sea sands indicates that there may be fewer organic constituents in them than in the sands of the slope from which they were derived. Admixture of deep- and shallow-water Foraminifera suggests that material has been picked up during the passage of the currents down the oceanic slopes. Much remains to be learned, however, before reliable interpretation of deepwater sand layers can be made.

Shales (Mudstones)

Various names have been applied to the sedimentary rocks which consist of grains of silt and clay (*20*), but the most common names are shale and mudstone or mud rock. Among the sedimentary rocks found on the continents, shale is generally considered to constitute more than 50 percent, whereas sandstone accounts for only about 20 percent. Just the opposite is found on the continental shelves, where sand covers more than half of the surface area and about 30 percent could be classified as mud—that is, silts and clays. This contrast constitutes something of an enigma, since so far as we know most sedimentary rocks were formed in shallow marine waters. The enigma is explained by the somewhat atypical nature of present-day shallow marine sediments. This, in turn, is due to the recent rise in sea level; many of the sands of the continental shelves are not yet covered by the muds derived from the continents. Furthermore, there were extensive shallow bays or epeiric seas in the past, and these are not well represented at present. If the continental glaciers of Antarctica and Greenland should melt, the rise in sea level would produce much larger embayments in which the protecting headlands would favor the deposition of fine-grained material to a greater degree than on the exposed continental shelves, where both waves and ocean currents interfere.

Continental shelf shales. To judge from available information, the chief areas of active deposition on the continental shelf have muddy sediments. Large areas on the continental shelf of the northwest Gulf Coast are mud-covered, and cores show that the muds are at least as thick as the length of penetration of the coring devices (10 or 20 feet). These deposits have little stratification, although they may develop fissility upon compaction. The chief fossils found in these shelf muds are Foraminifera. On the outer shelf, except near a delta, the Foraminifera are largely planktonic (the free-floating type of plankton). Nearer shore, on the other hand, the Foraminifera are largely benthonic—that is, bottom dwellers. Thus, these unicellular organisms often give a clue as to the part of the shelf on which they were deposited. Many of the benthonic Foraminifera dwell only at certain depths, and the range is limited. The sediments on the shelves off most of the large rivers are muddy, although the outer shelf, as explained previously, is usually covered with sand.

The coarse fraction of the shelf muds varies in composition from place to place, but it usually contains echinoid spines along with Foraminifera and small amounts of glauconite. Shell fragments are more common than in most other environments.

Muds of lagoons and estuaries. Most bays protected by sand islands receive mud deposits which are usually quite distinct from those of the open continental shelf. The echinoids and glauconite of the shelf muds are rare in the protected bays. Shells and Foraminifera are both found in typical bay deposits, but they differ considerably from those of the shelf. Among the shells, oyster shells are particularly common and often form reefs. In old bay deposits these reefs are frequently found cutting across the shales and mudstones. As for other shells, the bay deposits contain only a few species, in contrast to the diverse shell faunas of the shelf. In the Foraminifera found in bay deposits there are virtually no planktonic forms; as in the case of shells, the deposits usually contain only a few species.

The stratification is found to be poor wherever the bays support abundant burrowing organisms. The chief exceptions are bays where there are stagnant areas in the water mass, as in some bays with deep holes or in arid areas where there is little entering drainage. Stratification may also be preserved if the deposition is rapid. In arid bays the sand grains mixed with the mud are apt to have coatings of calcium carbonate, deposited as the result of evaporation.

Delta margin shales. The areas where mud deposition is going on most rapidly are at the margins of the large deltas (Fig. 4). At the mouths of the Mississippi, for example, mud is building up the slopes at rates of a foot or more per year (*21*) in contrast to typical shelf muds which have only accumulated a score of feet in the past 10,000 years or more since the sea came in over the outer shelf. This great contrast must have held also in the past. It is, therefore, somewhat puzzling that geologists have found so few shales to which they attribute a deltaic origin. Most of the old formations which are considered deltaic consist of sandstones, such as the Devonian Catskill sandstones of New York state that represent a great delta built into the sea from the old land of Appalachia.

Perhaps the scarcity of ancient mud deltas is explained by failure to recognize these deposits. Too much attention has been paid to the deltaic structure (Fig. 5), which geology textbooks show as a series of highly in-

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clined foreset beds built over the horizontal bottomset beds and in turn covered by horizontal topset beds. The foreset beds represent a deposit formed on and conforming to an already existing slope, whereas the bottomset beds develop on the flat bottom of the body of water and the topset beds are deposited above the forward-building inclined series. This diagram applies to many small lake deltas built largely of sand, but it does not apply to the large muddy deltas built into the ocean. These latter have foreset beds with very gentle inclinations, rarely over one-half degree; hence, the discordance between the bottomset, foreset, and topset beds is very slight and could easily be overlooked in rock formations.

Studies of modern deltas have shown other characteristics which would be of more use than deltaic structure in identification of the old deltas. Among these is the good development of lamination in the topset beds. In most cases the laminae represent alternation between clayey and sandy or coarse silt layers. Such lamination is common among ancient shales, and it may be that much of it is deltaic but has not been so recognized. The deltaic deposits have an abundance of wood fibers, since most rivers transport great quantities of wood to the sea. In the swamps bordering some river channels future thin coal beds may be forming. Fossils other than wood are scarce in deltaic deposits The rivers in general transport a great deal of mica; much of this is deposited at or near the river mouths, although it is also abundant in other environments. Small aggregated grains of orange or brown color are common in recent deltaic deposits and may be found as well in ancient ones.

Black shales. Geologists have been debating the origin of black shales for generations. The Chattanooga shale of the southern and midwestern states has been intensively investigated. In addition to being black, it is well laminated, although the laminae do not show the frequent alternation of fine and coarse sediment that is found in deltaic deposits. Presumably, few burrowing animals were present to disturb the layering. It is generally agreed that deposition conditions were those of stagnation. One group of geologists believes that the shale had a shallow-water origin and another group considers it a deepwater deposit. Among the findings which suggest that the water was shallow are the presence of ripple marks, the presence of occasional layers with cross-bedded sands, and the high degree of sorting. This, however, is not entirely convincing to marine geologists, since we have many photographs of ripples now forming in deep water and the

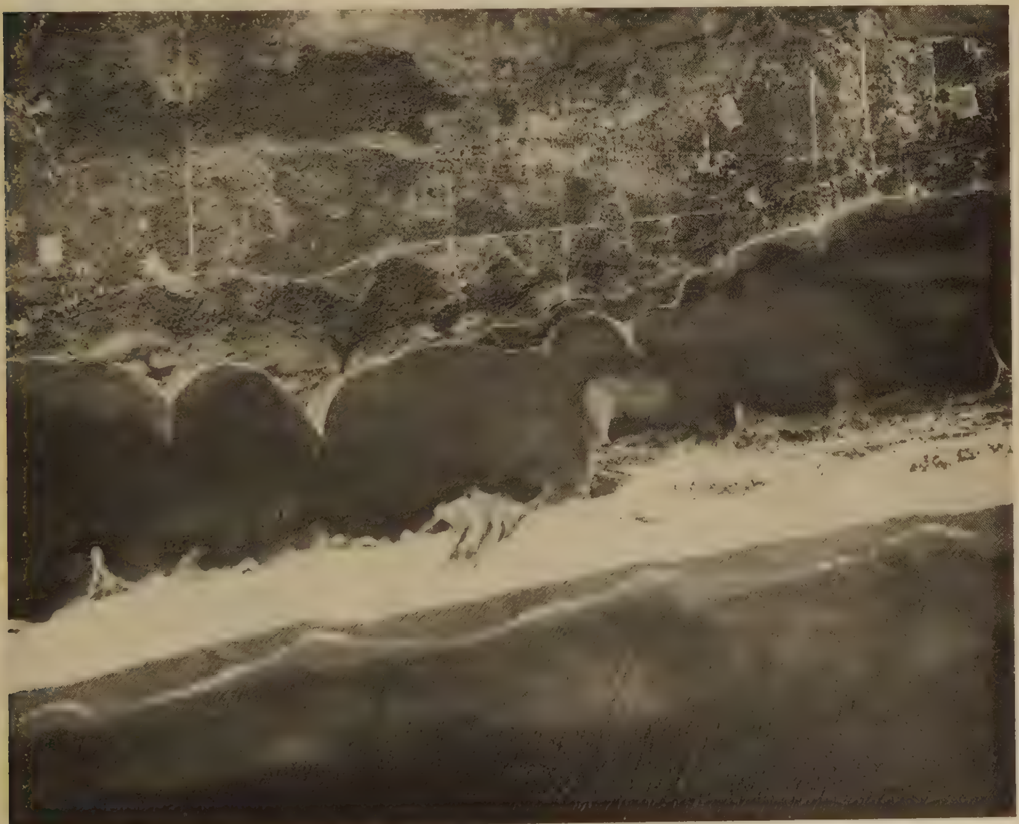
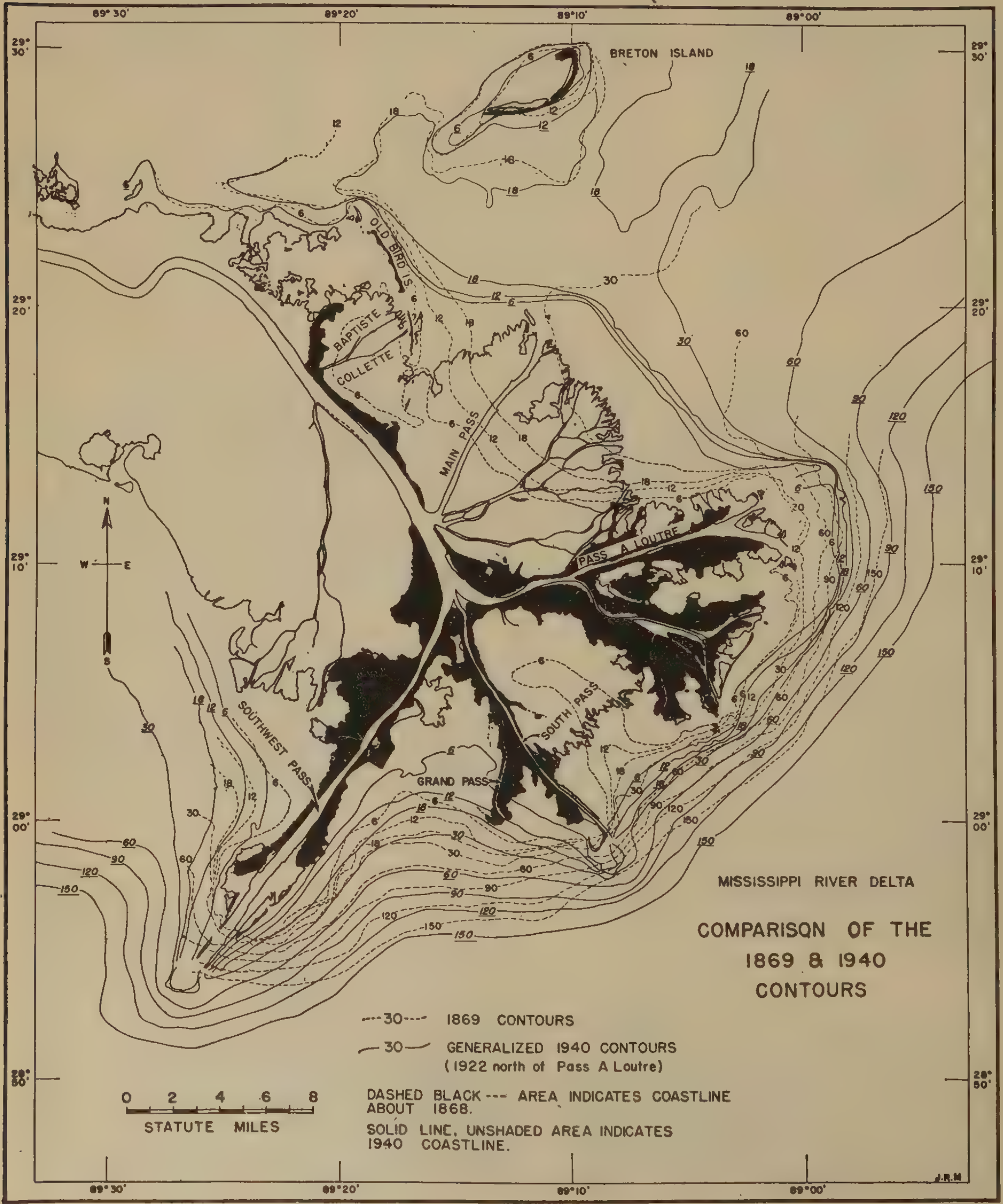


Fig. 3. A sandy barrier island along the coast of Alabama. Indications of overwashes into the lagoon are shown at several places, notably in the center. Underwater sand bars are indicated near the shore in clear water. [U.S. Coast and Geodetic Survey]

deepwater sediments include well-sorted and cross-bedded sands. A comparison with the deep floor of the Black Sea, where stagnant conditions exist at the bottom, is of interest, since the sediments include laminated black mud along with gray mud and calcareous deposits (*22*). On the other hand, the underlying unconformity and overlying shallow-water beds of the Chattanooga shale argue against deposition in such a deep basin. Black muds are also found in some of the fiord basins of Norway (*23*), where there is considerable depth of water. Here, however, we have a situ-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BRETON ISLAND
OLD BIRD IS.
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COLLETTE
MAIN PASS
PASS A LOUTRE
SOUTH PASS
SOUTHWEST PASS
GRAND PASS
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120
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MISSISSIPPI RIVER DELTA
COMPARISON OF THE 1869 & 1940 CONTOURS
---30--- 1869 CONTOURS
—30— GENERALIZED 1940 CONTOURS (1922 north of Pass A Loutre)
DASHED BLACK --- AREA INDICATES COASTLINE ABOUT 1868.
SOLID LINE, UNSHADED AREA INDICATES 1940 COASTLINE.
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Fig. 4. Contour map showing the great forward building of the Mississippi delta that occurred between 1869 and 1940. Depths are in feet.

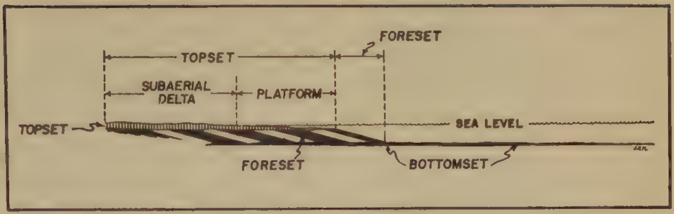

Fig. 5. Conventional diagram of a growing delta. Large marine deltas differ from this in having much lower foreset slopes.

ation resulting from overdeepening of valleys by glaciation, and there is no sign of glaciation in the Devonian, when the Chattanooga shale was deposited. Furthermore, the Chattanooga shale forms a widespread blanket rather than a deposit formed in a narrow trough. The same objection applies to comparison with the laminated black muds of Kaoe Bay in Indonesia (*24*). Black color in sediments has been found in such bays as the Bay of Danzig and elsewhere in the Baltic Sea (*25*), but here the black color is due to excess of organic matter rather than to stagnation, and burrowing animals exist which churn up the bottom. In fact, it seems likely that we have not yet discovered a modern environment which contains all of the characteristics of that which produced the laminated black shales.

Deep basin shales. The deep basins and troughs bordering the southern California coast represent another environment in which mud is accumulating although it is interlayered with turbidity-current sands. The muds are dark green in color. Except for the sand layers, stratification is poor, and there is virtually no lamination except in the relatively stagnant Santa Barbara basin. In the Gulf of California, on the other hand, some of the basin muds are well laminated, having alternate layers rich in diatoms. Here, although there is some circulation, burrowing organisms have not destroyed the stratification; this is probably due to the annual overturn in the gulf in winter, which brings an abundance of nutrients into the surface waters and results in great blooms of plankton. The diatoms are the chief planktonic contributor to the sediments. Comparison with the diatomite shales of Miocene age in California seems justified. These were probably also of deepwater origin, to judge from fossil fish fauna (*26*).

Limestones and dolomites. The chief carbonate rocks are called limestone when calcite ($CaCO_3$) is the dominant mineral and dolomite or dolostone when the mineral dolomite ($CaMgCO_2$) is most common. Among recent calcareous sediments, only calcium carbonate is found; this suggests that dolomite is formed later. If the carbonate sediments are fine-grained and poorly consolidated, the limestone is referred to as a chalk. These carbonate rocks are comparable to sandstones in their abundance among marine sedimentary rock formations. The study of recent sediments has shown that almost all of the present-day carbonate deposits are developing in the tropics or subtropics. Ancient limestones and dolomites are found at all latitudes, and this has been considered (no doubt with good reason) an indication either that the climates of the past were warmer than those of the present or that the pole or the earth's crust has been migrating so that localities now at high latitudes were formerly near the equator.

The calcareous rocks include a variety of types. These can be conveniently subdivided into fragmental limestones, reef limestones (commonly called bioherms), chalk and other fine-grained calcareous rocks, and oölites. Each of these has its counterpart in the present seas. Much information concerning these environments has come from studies sponsored by the American Museum of Natural History (*27*) and by the U.S. Geological Survey (*28*).

Fragmental limestones. Probably there are more limestones consisting of fragments of shells, corals, and other calcareous organisms than any other type. Similarly, on the sea floor there appear to be more fragmental calcareous deposits than any other kind (*29*). For example, most of the wide shelf off the west coast of Florida has a cover of shell sands and fragments of calcareous algae. It is thought that the shelf off Yucatan has a similar cover. Most of the tropical islands of the Pacific are bordered by shelves with calcareous detritus. This material is transported by the waves and currents very much as the quartz sands and other land-derived minerals are transported across the shelves in cooler climates. Bars like those of Nantucket Shoals are developed out of the fragmental lime debris; hence, limestones often have the cross-bedding characteristic of sand bars.

Reef limestones. Geologists have long recognized that many limestones had their origin as ancient coral reefs. Much of the early exploration of the oceans, including that of Darwin, was concerned with the coral islands. Although the present-day corals are quite different from those of the Paleozoic, some of the reef characteristics are found in the ancient reefs. The steep reef margins are clearly recognized in many Paleozoic reefs with highly inclined flanking layers made up of coral talus broken from the reefs by the waves. Many of the ancient reefs consist dominantly of calcareous algae, and this is also true of many reefs of today. Another characteristic of the ancient reefs is the general absence of stratification. This is due to the upward growth of the reef which accompanied the subsidence of the bank on which it was growing. The interlacing of the corals allows little stratification. The dolomites in the eastern Alps, with their structureless appearance, are said to represent an example of these ancient reefs, although most of the coral structure has disappeared because of the ease with which carbonate minerals recrystallize.

Chalk and fine-grained limestones. Chalk, which used to be used universally for writing on blackboards, is found to consist of an abundance of planktonic organisms, of which Foraminifera are an important constituent. For a long time it was thought that chalk was a deepsea deposit comparable to the *Globigerina* oozes. More careful study, however, showed that its benthic organisms are primarily shallow-water types. The plankton can accumulate in shallow water as well as in deep, provided they are not masked by other material. Some of the chalks of the southeast United States have been shown to consist of coccoliths (*30*), parts of a small planktonic lime-secreting plant. These plant remains are easily altered under pressure, and therefore old formations are not likely to preserve them. Other fine-grained lime deposits appear to have been deposited as the result of chemical precipitation from supersaturated waters. This was probably the origin of the lime muds of the Bahamas (*31*). Still other fine-grained limestone may have been formed in the deep waters at some distance from reefs, where only the finest reef debris has been transported to the site of deposition. Such fine-grained calcareous muds are found at depth around some oceanic reefs, but elsewhere the Foraminifera are so common that the sediments are relatively coarse, even at depth.

Oölitic limestone. Many limestones consist of small rounded grains looking like fish roe; hence the name, derived from *oö,* a shortening of the Greek *oion,* meaning egg. In section the oölites show concentric layers and, in some cases, a nucleus. These oölitic limestones are particularly common in the Jurassic of Europe, and it was the English who first called the rocks of this period the oölite series. Modern oölites are particularly well represented in the extensive Bahama banks (*32*). The spectacular underwater dunes, which can be seen so well through the clear water when one is flying over these banks, consist largely of oölites. These will undoubtedly produce limestones with much cross-bedding. The Bahama oölites are generally attributed to chemical precipitation which occurs when cool waters rise from the depths onto the warm banks, and the warming causes supersaturation. Deposition is especially active at the edges of the shallow platforms or along the edges of the tidal channels. The roundness is due in part to concentric deposition and partly to the rolling of the grains by the waves and currents. The unstable dune area is not favorable for the growth of bottom-dwelling organisms, and fossils in such deposits are relatively rare. This is apparent in the elevated oölites found on various islands in the Bahamas. In some areas oölites occur on the continental shelves as relics of former shallow-water conditions. This is particularly well illustrated by the outer shelf off western Florida (*33*). Oölites are not all marine formations. In fact, they develop very commonly in dry basins around lakes, such as Great Salt Lake.

Marine Conglomerates and Breccias

The sedimentary rocks containing an abundance of pebbles, cobbles, or boulders in a matrix of finer material are called conglomerates if the fragments are somewhat rounded and breccias if they are largely angular. Most conglomerates are land deposits, developing especially in the fans at the base of mountain slopes. Rivers carry pebbles into the sea, and various types of rock fragments are broken from cliffs, landing in the shallow adjoining seas, but in neither case are extensive marine conglomerates likely to develop. This is partly because the waves in shallow water grind up the large fragments into sand or finer material and because the waves are not capable of carrying the pebbles out far from the shore. In fact, waves tend to work the coarser material in towards shore, building it up as rampart beaches.

There are, however, many conglomerates and breccias which lie interbedded between formations that have marine shells and, in some cases, deepwater assemblages. The Flysch formation in the Alps is notable for such an alternation between conglomerates or breccias and deepwater mudstones. Their origin is not quite certain. Some of the conglomerates grade upward into fine material and hence their presence has been attributed to turbidity currents (*34*). Others include boulders, some of them as big as a house, and do not appear to be due to turbidity currents, since they lack all signs of graded bedding. These Alpine breccias, and probably also many of the ungraded conglomerates, can be explained by a type of submarine slope failure which has allowed the rocks from the upper slope or even from the adjacent mountain walls to catapult down the sides of a deep basin and come to rest on top of the fine-grained basin sediments. The fine sediment in the interstices between the large fragments may consist of deep-sea deposits introduced after the slides occurred. Such conglomerates have been found at the base of the cliffs outside the Yucatan shelf (*35*). They are also well illustrated in the Pliocene formations of Ventura County, California (*36*), and in western Venezuela (*37*).

The study of submarine slopes has shown that many of them are very unstable (*38*). They are particularly likely to slide at the time of an earthquake. Many cable breaks have resulted either from these slides or from turbidity currents (*39*).

Other kinds of marine conglomerates and breccias may be formed through the rafting of rock fragments, although the "plums" in this type of "puddingstone" are apt to be few and far apart. The most important means of floating rocks out into the sea is by icebergs or drift ice. In the areas where there are many icebergs, as around Antarctica, the sea floor is littered with pebbles. This produces what is called a glacial marine sediment. Such sediments are found beneath the most recent sediments in the cores of the North Atlantic (*40*), representing the glacial stages of the Pleistocene, when icebergs were more common. On a smaller scale pebbles are rafted out by vegetation, especially beyond the mouths of tropical rivers. Also kelp, when broken off by the waves, often carries rock fragments in its rootlike holdfasts, and enough may be accumulated this way to make a local conglomerate.

Concluding Remarks

The foregoing suggestions regarding the origin of marine sedimentary rocks must be considered as partly speculative because they are based largely on investigations that are far from complete, and vast areas of the sea floor have not been explored at all by marine geologists. The introductory studies, however, seem to have shown that many of the old ideas about marine sedimentation are outmoded. Thus, sandstones and even conglomerates are not confined to shallow water, as was formerly supposed, but can form in deep water provided there are relatively steep slopes down which slides and turbidity currents may transport the material to the deeps. Similarly, the ripple marks and cross-bedding, formerly supposed to indicate shallow-water origin, have now been found also in deepwater sediments. We are still looking for the most reliable criteria for distinguishing between the deepwater and shallow-water sands, although graded bedding has already proved somewhat helpful when related to the occurrence of deepwater organisms in the underlying and overlying beds.

On the continental shelf so many exceptions have been found to the old concept that fine sediments are deposited outside of, and in deeper water than, coarse sediments that determination of grain size as a means of "finding the shoreline"—a method used so much by geologists—seems open to reexamination. On the continental shelves many of the sand zones outside deposits of mud appear to be relics of a period of lower sea level, but currents of sufficient strength to transport sand are found on the outer shelves in many places. Therefore, sand formations may be deposited on the continental shelf contemporaneously with, and yet farther from shore than, mud formations, and the two may have different geological sources.

The frequent occurrence of mud deposits around the advancing margins of modern deltas and the very infrequent occurrence of ancient shales considered to be deltaic suggests that some or many ancient deltas may not have been recognized. The characteristics found in the sediments around the margin of the Mississippi and other great deltas should prove helpful in recognizing such deposits among rock formations. Similarly, the various types of calcareous deposits found on the shelves and banks of the world are providing means for determining the conditions under which the limestones now on the continents were deposited.

In concluding, it should be emphasized that the study of recent sediments can at best provide some useful clues which help us to interpret the past. The thoroughgoing field examination of stratigraphic relationships will still be the most important method available to the geologist.

References and Notes

1. Among the books published as a result of these studies are P. D. Trask, *The Origin and Environment of Source Sediments of Petroleum* (Gulf, Houston, Texas, 1932); ———, Ed., *Recent Marine Sediments, a Symposium* (Am. Assoc. Petrol. Geologists, Tulsa, Okla., 1939).
2. Among the results published to date are F. P. Shepard and D. G. Moore, *Soc. Econ. Paleontol. and Mineral. Spec. Publ. No. 3* (1955), pp. 78–96; P. C. Scruton, *Bull. Am. Assoc. Petrol. Geologists* 40, 2864 (1956); R. H. Parker, *ibid.* 40, 295 (1956); F. B. Phleger, *Cushman Foundation for Foraminiferal Research* (1956), vol. 7, part 4, pp. 106–151; F. P. Shepard, *Bull. Am. Assoc. Petrol. Geologists* 40, 2537 (1956).
3. Tj. H. van Andel and H. Postma, *Reports of the Orinoco Shelf Expedition* (1954), vol. 1; D. J. G. Nota, *Reports of the Orinoco Shelf Expedition* (1958), vol. 2; G. W. Koldewijn, *Reports of the Orinoco Shelf Expedition* (1958), vol. 3.
4. K. O. Emery, J. I. Tracey, Jr., H. S. Ladd, *U.S. Geol. Survey Profess. Paper No. 260-A* (1954).
5. K. O. Emery and S. C. Rittenberg, *Bull. Am. Assoc. Petrol. Geologists* 36, 735 (1952); W. L. Orr, K. O. Emery, J. R. Grady, *ibid.* 42, 925 (1958).
6. N. M. Strakhov *et al.*, *The Formation of Sediments in Recent Basins* (Academy of Sciences of the U.S.S.R., Moscow, 1954).
7. *Geol. Rundschau* 47, 24 (1958).
8. B. Kullenberg, *Svenska Hydrograf.-Biol. Komm. Skrifter, Ny Ser. Biol.* 1, 1 (1947).
9. Illustrated in H. S. Ladd, *Science* 129, 69 (1959), Fig. 4.
10. The term *scuba* is coined from the words "self-contained underwater breathing apparatus."
11. J. Y. Cousteau, *National Geographic* 113, 373 (1958).
12. N. W. Bass, *Bull. Am. Assoc. Petrol. Geologists* 18, 1313 (1934).
13. R. H. Nanz, Jr., *ibid.* 38, 96 (1954); J. R. Curray, *J. Geol.* 64, 117 (1956).
14. E. D. McKee, *J. Geol.* 47, 64 (1939).
15. M. A. Beal and F. P. Shepard, *J. Sediment. Petrol.* 26, 49 (1956).
16. P. H. Kuenen and C. I. Migliorini, *J. Geol.* 58, 91 (1950).
17. K. Terzaghi, *Proc. Texas Conf. on Soil Mechanics and Foundation Engineering, 8th Conf.* (1956).
18. D. B. Ericson, M. Ewing, B. C. Heezen, G. Wollin, *Geol. Soc. Am. Spec. Paper No. 62* (1955).
19. Other features such as "fluting" and "involute structures," found in ancient sandstones, which are supposed to be of turbidity-current origin, have not yet been recognized in the sea-floor sediments.
20. Silt is usually defined by geologists as sedimentary rock in which the grains range from 1/16 to 1/256 millimeter in diameter; clay, as that composed of finer particles, including colloidal material.
21. F. P. Shepard, *Bull. Geol. Soc. Am.* 66, 1489 (1955).
22. L. P. Smirnow, in *Habitat of Oil, a Symposium* (Am. Assoc. Petrol. Geologists, Tulsa, Okla., 1958), p. 982; a compilation from many sources.
23. K. M. Strøm, in *Recent Marine Sediments* (Am. Assoc. Petrol. Geologists, Tulsa, Okla., 1939), p. 356.
24. P. H. Kuenen, *The Snellius Expedition* (1942), vol. 5, part 3, p. 28.
25. C. O. Dunbar and J. Rodgers, *Principles of Stratigraphy* (Wiley, New York, 1957), p. 205.
26. L. R. David, *Geol. Soc. Am. Spec. Paper No. 43* (1943).
27. N. D. Newell, *Bull. Am. Museum Natl. Hist.* 109 (1956).
28. K. O. Emery, J. I. Tracey, Jr., H. S. Ladd, *U.S. Geol. Survey Profess. Paper No. 260-A* (1954).
29. C. O. Dunbar and J. Rodgers, *Principles of Stratigraphy* (Wiley, New York, 1957), p. 274.
30. M. N. Bramlette, *Bull. Geol. Soc. Am.* 69, 121 (1958).
31. L. V. Illing, *Bull. Am. Assoc. Petrol. Geologists* 38, 1 (1954).
32. ———, *ibid.* 38, 35 (1954).
33. H. R. Gould and R. H. Stewart, *Soc. Econ. Paleontol. and Mineral. Spec. Publ. No. 3* (1956), p. 2.
34. P. H. Kuenen, *J. Geol.* 61, 363 (1953).
35. M. Ewing, D. B. Ericson, B. C. Heezen, in *Habitat of Oil, a Symposium* (Am. Assoc. Petrol. Geologists, Tulsa, Okla., 1958), Fig. 27.
36. M. L. Natland and P. H. Kuenen, *Soc. Econ. Paleontol. and Mineral. Spec. Publ. No. 2* (1951), p. 76.
37. O. Renz, R. Lakeman, E. Van der Meulen, *Bull. Am. Assoc. Petrol. Geologists* 39, 2053 (1955).
38. K. Terzaghi, *Proc. Texas Conf. on Soil Mechanics and Foundation Engineering, 8th Conf.* (1956).
39. B. C. Heezen and M. Ewing, *Am. J. Sci.* 250, 849 (1952).
40. M. N Bramlette and W. H. Bradley, *U.S. Geol. Survey Profess. Paper No. 196* (1942), part 1.

REPORTS OF THE SWEDISH DEEP-SEA EXPEDITION. VOL. VIII
SEDIMENT CORES FROM THE MEDITERRANEAN SEA AND THE RED SEA. NO. 4

EASTERN MEDITERRANEAN FORAMINIFERA

BY

FRANCES L. PARKER

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Summary

1. A study has been made of Foraminifera in 16 long cores from the eastern Mediterranean Sea and 60 surface sediment samples from the eastern Mediterranean and Aegean seas. In an appendix, 110 benthonic species are discussed of which the following are new: *Bolivina attica*, *Epistominella rugosa convexa*, *Gyroidina delicata*, and *Rotamorphina? involuta*; 18 planktonic species are discussed of which one is new: *Globigerinoides tenella*.

2. The surface water layer, derived from the western Mediterranean, is about 200 m. deep, the intermediate water layer about 200—700 m., the transition (to deep) water layer 700—1600 m., the deep water layer, derived from the Adriatic Sea, 1600 m. and deeper. Mean surface water temperatures are 16—24° C in the Ionian Basin, 16—29° C in the Levantine Basin and 12—25° C in the Aegean Sea, with minimum temperatures in February-March and maximum in July—August. In all areas the temperature variation decreases with depth down to 500 m. (and deeper) where it is *ca.* 1° (13—14° C). Surface water salinities in the eastern Mediterranean are *ca.* 38 ‰ except at nearshore stations where they may be much lower due to local conditions. In the Aegean they are *ca.* 30 ‰ in the north and 39 ‰ in the south near Crete. Deeper salinities in the whole area are near 38—39 ‰.

3. Planktonic Foraminifera are found in all surface sediment samples except the one from Piraeus Harbor. Progressing from shallow

to deep water the species appear approximately in the order of their frequency in deep sediments. An exception is *Globigerina pachyderma* postulated to be a deep-living species. The ratio of planktonic population to total foraminiferal population increases from 3 % at 51 m. to 21—98 % deeper than 500 m., and greater than 99 % deeper than 1300 m.

4. The modern planktonic fauna is probably largely indigenous due to a barrier near Gibraltar caused by a temperature change and/or other factors. Species present in the adjacent Atlantic are absent in the Mediterranean and vice versa. This applies also to core faunas in the two areas. In the eastern Mediterranean the fauna shows an increase in warm-loving species over the western due to the higher temperatures obtaining there. In the Aegean Sea the faunas reflect the cooler conditions.

5. In the surface sediments four depth assemblage boundaries based on benthonic species are found: bay-open ocean, 143—205 m., 500—700 m., and 1000—1300 m. Except for the first, these boundaries coincide approximately with the water layer boundaries. The assemblages are similar to those of other areas at analogous depths except for the deepest one which contains an unusually sparse fauna.

6. Badly preserved, glauconite-filled specimens give evidence of non-depositional conditions at some localities. Displaced shallow species are found at some deep stations near coastal areas.

7. Benthonic populations in the cores are relatively small, the largest being in core sections believed to reflect cooler climates or sections containing specimens displaced from shallow water. »Floods» of species such as *Bulimina aculeata*, *Globobulmiina*? sp. and *Pyrgo serrata* occur occasionally. The most common species are *Articulina tubulosa* and vars. and *Miliolinella circularis*. Displaced shallow specimens are most common in cores near shallow coastal areas.

8. The planktonic populations in the cores are usually large and show little solution of calcium carbonate tests. It is suggested that sections containing few or no planktonic specimens represent times of rapid sedimentation. The top samples of most cores contain faunas analogous to the modern ones although the upper sections (less than one meter) may be missing. Constituents of the faunas believed to reflect climatic temperature variations have been analyzed. The »warm» fauna which reflects relatively warm conditions consists of *Globigerinella aequilateralis*, *Globigerinoides rubra* s. s., *G. sacculifera*, and *Hastigerina pelagica*. The »cold» fauna which reflects relatively cooler conditions consists of *Globigerina pachyderma* and *Globorotalia scitula*. Other species also appear to reflect temperature changes but this has not yet been observed for these species in other areas. The frequencies of such species as *Globigerina eggeri* and *G. inflata* appear to reflect, to a great extent, factors other than temperature. In most cores the planktonic faunas reflect the occurrence of two long cold intervals separated by a short warm one and preceded (in time) by a long fluctuating warm interval.

9. *Globorotalia truncatulinoides* is left-coiling in the modern sediments. In the cores it shifts to right coiling shortly above the end (in time) of the uppermost cold interval. Occurrences are sparse but show several fluctuations in the cores down to the lower part of the second long cold interval (from the top) where the species is much commoner and the direction of coiling fluctuates several times. In the long warm interval below it is even more abundant and coiling direction fluctuates more frequently.

10. The temperatures calculated from isotopic data for Core 189 by Emiliani (1955 b) show fluctuating curves very similar to those of the »warm» and »cold» planktonic faunas. It is suggested that the absolute temperature values obtained by isotopic nethods may be invalid due perhaps to the presence of Zooxan-

thellae in the living forms which may exchange oxygen with the calcium carbonate test of the host.

11. It is suggested that the two long cold intervals reflected by the planktonic core faunas represent the Last Glaciation (Würm I, II, III) and the long warm interval preceding them the Last Interglacial (Riss/Würm). A comparison is made with the previous interpretation of Emiliani (1955 b).

12. Correlations of the cold and warm intervals made between cores agree well with correlations made by other workers using other criteria. An exception is the upper volcanic ash bands correlated by Mellis (1954) between cores 187, 188, 189, and 192. The bands in cores 187 and 188 do not appear to correlate with those of cores 189 and 192.

13. The upper sections of a few cores contain a »warm» fauna having a higher frequency than that of modern sediments. This is postulated to reflect the »Climatic Optimum» of ± 5000 years B. P. Sedimentation rates are calculated using this event, the published radiocarbon date for Core 189 of 17200 ± 500 years B. P. and the points in the cores reflecting the various postulated climatic events. These rates vary from 22.1 cm./1000 years in the upper part of Core 184 (situated near the Nile Delta) to 5.7 cm./1000 years in that of Core 194. The calculated rates vary in different parts of the cores and it is suggested that they are highly speculative and that uniform sedimentation cannot be assumed even for short core sections. The highest rates occur in cores 184, 198, and 199.

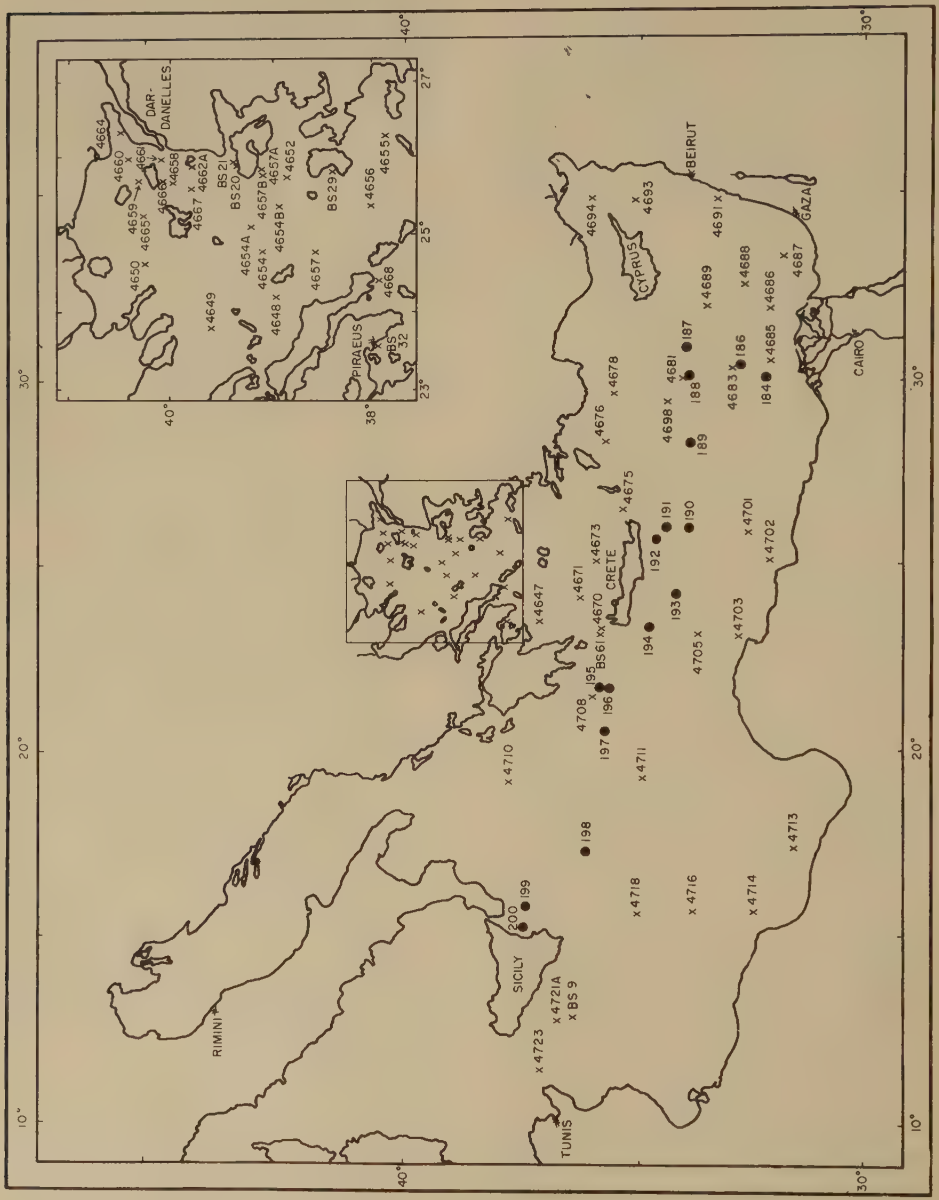
Introduction

This is one of a series of papers on the Foraminifera from long cores collected by the Swedish Deep-Sea Expedition under the leadership of Prof. Hans Pettersson. It is chiefly concerned with the study of sixteen cores collected under the personal supervision of Prof. Börje Kullenberg in the eastern part of the Mediterranean Sea. In addition, it includes a study of the Foraminifera in sixty surface sediment samples collected in 1948 in the eastern Mediterranean and Aegean seas by the Woods Hole Oceanographic Institution using the Research Vessel ATLANTIS. The writer wishes to give especial thanks to Profs. Pettersson and Kullenberg for their generosity in providing the material from the long cores and assisting in various ways. Thanks are also due to the members of the Woods Hole Oceanographic Institution who provided the surface sediment samples. Mrs. Jean Peirson Hosmer drafted the illustrations and assisted with the laboratory work. This study has been supported by the University of California under contract with the Office of Naval Research.

The purposes of this study are two-fold. The first is the analysis and interpretation of the Foraminifera in surface sediments at various depths. The depth distributions of the various benthonic forms are defined and faunal limits delineated. Further work on the planktonic forms is discussed to augment the results of a previous study (Parker, 1955). It was felt that this work on surface sediments would aid in the study of the long ceras which is the second and main purpose of the paper. This includes the analysis and interpretation of the foraminiferal distributions in the long cores, leading in turn to a discussion of the age and correlation of the sediments. Detailed core descriptions and a section on the systematics of the Foraminifera are given in Appendices A and B respectively.

Locations of Cores and Surface Sediment Samples

The core stations are located along an irregular line starting near the east coast of Sicily and extending eastward south of Crete to a position north of the Nile Delta, turning south


40°
30°
20°
10°
27°
25°
23°
38°
DAR-DANELLES
PIRAEUS
BEIRUT
GAZA
CAIRO
CYPRUS
CRETE
SICILY
RIMINI
TUNIS
4664
4660
4661
4659
4665
4666
4658
4662A
4667
4650
BS 21
BS 20
4657B
4657A
4652
4654A
4654
4654B
4649
4648
4657
4656
4655
BS 29
4668
BS 32
4694
4693
4691
4689
4688
4687
4686
4685
4683
4681
4678
4676
4698
4675
4673
4671
4670
BS 61
4647
4701
4702
4703
4705
4708
4710
4711
4713
4714
4716
4718
4721A
BS 9
4723
184
186
187
188
189
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198
199
200

Figure 1. Locations of cores (0) and surface sediment samples (X).

(326)

at this point towards the delta. The surface sediment stations are more widely scattered in an area extending from south of Sicily in the west almost to the coast of Israel in the east and northwards into the Aegean Sea, where most of the shallow samples were taken. They range in depth from *ca.* 25 m. to 4667 m. The locations are shown in Figure 1; exact positions and depths are given in Table 1. Koczy (1956, profile 16) gives bottom topography profiles of the core station areas.

Methods of Study

The cores, varying in length from 0.8—11.49 m., were taken with the piston coring tube developed by Kullenberg (1947). They were split in half vertically and samples 0.5 cm. in thickness were taken at approximately 10 cm. intervals. The samples were then trimmed to remove contaminated material caused by drag on the outside of the cores. This procedure was carried out by members of the Oceanografiska Institut in Göteborg. These samples, taken from cores having a diameter of *ca.* 4.5 cm., contain about 7 cu. cm. of sediment. Phleger, Parker, and Peirson (1953) give an average weight of such samples (before washing) of 3 gm. The fine sediment was washed from them through a brass sieve with *ca.* 0.074 mm. openings.

The foraminiferal assemblages of all the core samples were examined but population counts were made only at approximately 50 cm. intervals, including top and bottom samples, unless intervening ones showed faunal change by gross examination. The population counts were made from screened samples obtained by using a sieve with openings of *ca.* 0.149 mm. These were divided with a microsplit (Parker, 1948, p. 218) to give a working sample of approximately three hundred planktonic specimens. The entire sample (> 0.149 mm.) was used in counting the benthonic forms since in most cases they are relatively rare. For this reason on Tables 6—20 benthonic occurrences are given in numbers of specimens rather than in per cent pf total benthonic fauna but the planktonic occurrences are in per cent of total planktonic populations.

The surface sediment samples, with a few exceptions, were taken with a short gravity corer. Sta. B. S. 32 was sampled with an underway bottom sampler, stas. 4649 A, 4657, and B. S. 21 A with an orange peel dredge, and Sta. B. S. 61 with a clam shell sampler. The fine sediment had been removed before we received the material so that equal sized samples could not be used. For this reason estimated total populations are not given in Tables 2 and 3. This is not important since the chief purpose of this part of the study is to obtain data on depth distributions of the species and frequency data on modern planktonic faunas in deep-water sediments for comparison with the core faunas. The technique used in making the population counts is similar to that described for the cores.

TABLE 1. Locations of cores and surface sediment samples.

Cores

No.	N. Latitude	E. Longitude	Depth (m.)
184	32° 12′	30° 13′	1176
186	32° 47′	30° 33′	2025
187	33° 59′	31° 02′	2500
188	33° 55′	30° 17′	2810
189	33° 54′	28° 29′	2664
190	33° 54′	26° 10′	2900
191	34° 24′	26° 11′	3635
192	34° 36′	25° 29′	2680
193	34° 12′	24° 22′	2130
194	34° 48′	23° 29′	3000
195	35° 52′	21° 53′	3665
196	35° 41′	21° 50′	4270
197	35° 47′	20° 42′	2940
198	36° 13′	17° 28′	3555
199	37° 29′	15° 58′	2370
200	37° 33′	15° 24′	2050
Surface sediment samples (from ATLANTIS cruise 151)			
4647	37° 09′	23° 38′	366
4648	38° 56′	24° 18′	338
4649	39° 35′	23° 53′	1265

No.	N. Latitude	E. Longitude	Depth (m.)
4649 A	40° 23′	25° 25′	106
4650	40° 14′	24° 42′	859
4652	38° 50′	25° 52′	201
4654	39° 04′	24° 54′	746
4654 A	39° 12′	25° 13′	115
4654 B	38° 54′	25° 29′	143
4655	37° 50′	26° 25′	1102
4656	37° 59′	25° 31′	680
4657	38° 32′	24° 54′	384
4657 A	39° 05′	25° 58′	104
4657 B	39° 04′	25° 56′	256
4658	39° 58′	25° 47′	82
4659	40° 18′	25° 45′	850
4660	40° 24′	26° 02′	665
4661	40° 05′	26° 04′	75
4662 A	39° 47′	26° 00′	51
4664	40° 28′	26° 25′	658
4665	40° 15′	25° 18′	1587
4666	40° 04′	25° 46′	71
4667	39° 47′	25° 41′	86
4668	37° 54′	24° 33′	117
4670	35° 49′	23° 27′	996
4671	36° 16′	24° 18′	1016
4673	35° 55′	25° 16′	1834
4675	35° 21′	26° 40′	1064
4676	35° 46′	28° 28′	3974
4678	35° 34′	29° 49′	1862
4681	34° 03′	30° 12′	2852
4683	32° 59′	30° 28′	2358
4685	32° 06′	30° 41′	647
4686	32° 06′	32° 05′	799
4687	31° 49′	33° 29′	631
4688	32° 42′	32° 43′	1312
4689	33° 32′	32° 09′	2442
4691	33° 17′	34° 59′	1331
4693	35° 08′	34° 56′	1073
4694	36° 02′	35° 03′	567
4698	34° 24′	29° 34′	2738
4701	32° 33′	26° 03′	2760
4702	32° 05′	25° 16′	799
4703	32° 48′	23° 13′	552
4705	33° 44′	23° 18′	1788
4708	36° 01′	21° 37′	3499
4710	37° 49′	19° 19′	3241
4711	34° 58′	19° 24′	3309
4713	31° 37′	17° 32′	684
4714	32° 30′	15° 49′	665
4716	33° 52′	15° 47′	1378
4718	35° 06′	15° 44′	541
4721 A	36° 49′	12° 54′	179
4723	37° 11.7′	11° 33.5′	567
B. S. 9	36° 28′	12° 55′	731
B. S. 20	39° 19′	26° 00′	210
B. S. 21 A	39° 21′	26° 03′	205
B. S. 29	38° 23′	25° 56′	287
B. S. 32	Piraeus Harbor		*ca.* 25
B. S. 61	35° 51′	23° 16′	462

Foraminifera in Surface Sediment Samples

Temperature and Salinity

The discussion given below is an emendation of one given previously (Parker, 1955). The eastern Mediterranean is separated from the western by a sill, between Sicily and Tunis, having a maximum depth of about 320 m. Water flows into the eastern basin as surface currents, returning westward at intermediate depths. The depth of the surface layer is about 200 m. The deep water according to Pollak (1951) is derived entirely from the Adriatic Sea and not from the Aegean as was previously believed. A comparison of the temperature, salinity, and dissolved oxygen curves for two stations, one in the Ionian Basin, and one in the Levantine Basin, show that above about 1000 m. the curves show great dissimilarity while below this depth they are similar. Pollak says in elaboration (*op. cit.* p. 132), »If the upper limit of the deep water were defined by marked changes in the gradients of the elements plotted, a depth of about 700 m. is the boundary layer. On the other hand, if absolute values are used as criteria, 1600 m. gives a rigorous upper limit for the deep water.» He considers the depth zone from 700—1600 m. one of transition between intermediate and deep water. He shows that the deep water derived from the Adriatic Sea is a mixture of relatively fresh water, largely river effluent from the northern Adriatic, and of Ionian Sea water of relatively high salinity from intermediate depths.

Surface currents enter the Aegean Sea from the Mediterranean to the southeast and the Black Sea to the northeast setting up a counterclockwise surface circulation.

In the eastern Mediterranean surface temperatures vary from 16° C to 24° C in the Ionian Basin to the west and 16° C to 29° C (Rouch, 1945) in the eastern part of the more easterly Levantine Basin, the lowest temperatures occurring in February—March and the highest in July—August. South of Sicily a winter maximum of *ca.* 14° C is reached (Guyot, 1951). Surface salinities vary from *ca* $38^0/_{00}$ in the west to *ca* $39.5^0/_{00}$ in the east although local variations may occur nearshore such as a salinity of $30\,^0/_{00}$ found near Gaza, Israel, in September, 1947, probably due to a Nile flood (Oren, 1952). Surface temperature in the Aegean Sea vary from *ca.* 12—25° C, surface salinities from *ca.* $30\,^0/_{00}$ near the Dardanelles (or even lower nearshore, Rouch, 1940) to $39\,^0/_{00}$ north of Crete.

There is less detailed information on salinities and temperatures in deeper water. Most of the following dato are taken from the *Bulletin Hydrographique, Copenhagen,* (1952) for the year 1948 and *Praktika of the Hellenic Hydrobiological Institute, vol.* 3, *no.* 3, *Piraeus* (1949) for the years 1947 and 1949. Temperatures for depths from 25 m. to 500 m. in the Aegean Sea, where most of the samples shallower than 500 m. were obtained, are:

Depth in Meters	Temperatures °C	
	Max.	Min.
25	11	21—
50	12+	21—
100	13+	18—
200—300	13+	16
400	14+	15
500	*ca.* 14	*ca.* 14

Deeper than 500 m. temperatures in both the eastern Mediterranean and Aegean seas are 13—14° C.

Salinities of water deeper than 25 m. in the southern Aegean and eastern Mediterranean usually vary between $38\,^0/_{00}$ and slightly greater than $39\,^0/_{00}$. This is not true, however, of all nearshore stations, especially in the northern Aegean where salinities of $37\,^0/_{00}$ or even less may occur at 25 m. due to the outflowing Black Sea water. In such cases there is a rapid increase deeper so that at 100 m. salinities are greater than $38\ /_{00}$.

Planktonic Foraminifera

General statement. The characteristics of the planktonic faunas of the deep-water surface sediments have been given previously (Parker, 1955). Since then two additional species have been recognized: *Globigerina radians* Egger and *Globigerinoides tenella,* n. sp. The systematic discussion of all the species is given in Appendix B. Data on the shallow-water samples (< 500 m.) and emended data on two deep-water samples are given in Table 2. in per cent of total planktonic population. In addition, for each station the per cent of planktonic to total foraminiferal population is given. Sta. B. S. 61 is omitted since there is evidence of large-scale faunal displacement from shallow water at that locality.

Planktonic specimens are found at all the shallow Aegean Sea stations except that in Piraeus Harbor. At 51 m. they form 3 % of the total foraminiferal population. This percentage increases with depth until a maximum of 99 % is reached at about 1300 m. Variable amounts occur deeper than 500 m. (21—98 %).

The order of appearance of planktonic species from shallow to deep water is as follows: at 51 m. *Globigerina bulloides, G. inflata,* and *Globigerinoides rubra;* at 71 m. *Globigerina digitata, G. quinqueloba,* and *Globigerinoides tenella;* at 75 m. *Globigerinoides sacculifera* and *Orbulina universa;* at 82 m. *Globigerina eggeri;* at 86 m. *Globigerinita glutinata;* at 104 m. *Globigerinella aequilateralis;* at 143 m. *Hastigerina pelagica;* at 287 m. *Globigerina radians;* at 338 m. *G. pachyderma;* at 366 m. *Globorotalia truncatulinoides* (rare in Aegean Sea); and at 859 m. *G. scitula* (rare in Aegean Sea).

The planktonic faunas of the two deep stations (Table 2) are believed to be typical of the faunas found at the two extremities of the eastern Mediterranean. They are given for comparison with the »top» faunas of the long cores. There is some variation in the populations of the deep-water sediment samples (*vide* Parker, 1955) but those at stas. 4681 and 4711 appear to be representative and contain fresh-looking specimens of apparently modern deposition. Sta. 4711 has the more complete fauna but rare occurrences not previously observed are listed for sta. 4681. Such occurrences are spasmodic and their inclusion in population counts of 300 specimens is a matter of chance. *Globigerinoides tenella* was previously included in *G. rubra* which now has a somewhat lowered frequency. »*G. rubra*, etc.» in Table 2 contains more than one species (*vide G. rubra* in Appendix B) but *G. rubra* s. s. makes up a large part of the specimens. *Globigerinella aequilateralis* has an increased frequency in the population recounts due to a greater understanding of the juvenile forms, some of which were previously included in other species. Further work on the life histories of the planktonic forms will undoubtedly lead to an even greater understanding of juvenile specimens.

Discussion. The modern planktonic fauna is similar to the core faunas believed to reflect the warmer climates of interglacial or interstadial times. The latter, however, vary in degree. As stated previously (Parker, 1955) the modern fauna is warmer in type than that of the western Mediterranean as shown by an increase in the frequencies of *Globigerinoides sacculifera* and *Hastigerina pelagica* and the decreased frequencies of *Globigerina bulloides*, *G. inflata*, and *Globorotalia truncatulinoides*. The Aegean Sea fauna, on the other hand, reflects the somewhat cooler conditions found there by the decreased frequencies of *Globigerinoides sacculifera* and *Globigerinella aequilateralis* and the increased frequency of *Globigerina bulloides*. The strong increase of *G. eggeri* frequencies shown earlier (Parker, 1955) is now believed to be erroneous since many of the small specimens originally identified as *G. eggeri* are now interpreted as atypical forms of *G. bulloides*.

The higher temperatures of the eastern Mediterranean have not led to the introduction of species found in the Atlantic west of Gibraltar, which are believed to be excluded from the western Mediterranean because of the decrease in surface water temperatures. These are *Globorotalia hirsuta*, *G. punctulata*, and *Pulleniatina obliquiloculata*. On the other hand, *Globigerinoides conglobata* which is also absent in the western area is found rarely in the eastern and occurs frequently in the long cores. The fauna appears to be largely an indigenous one and even the »warmest» core faunas do not contain species which might be expected if they were not excluded by some barrier. Examples are *Pulleniatina obliquiloculata* and *Globorotalia menardii*. The former does not occur in the adjacent Atlantic at the present time but is found in Core 215 which was taken near the Canary Islands (Phleger, *et al.*, 1953). Similarly *P. obliquiloculata* is found in surface sediments and cores in the adjacent Atlantic. That the barrier is not necessarily caused by temperature changes is shown by the presence in the Mediterranean of *Globigerina quinqueloba* and *Hastigerina pelagica*, both absent west of Gibraltar. The former prefers warm water, the latter cold. It is possible that future work will show that they have been overlooked in the Atlantic area.

The order of appearance of the species in sediments ranging from shallow-water to deep-water is approximately analogous to their frequency in deep samples. This means that the most common species appear first in the shallowest stations: *Globigerina bulloides* and *Globigerinoides rubra*. These are followed quickly by *Orbulina universa* and *Globigerinoides sacculifera*. Some exceptions to this rule occur, however: *Globigerina digitata*, a relatively uncommon form, is one of the first to appear whereas *G. pachyderma* which is relatively common does not occur until a depth of 338 m. It is suggested that the latter species may live in a deeper layer of water than most other planktonic species.

Benthonic Foraminifera

General statement. There have been many publications on the benthonic Forminifera of the western Mediterranean but very few on those of the eastern area. The latter are entirely descriptive, dealing with the systematics of the species with little or no data on distribution, and were written in the early days of foraminiferal study. Batsch (1791), Fichtel and Moll. (1798), d'Orbigny (1826) and Fornasini (various papers) described the fauna of Rimini, Italy. This fauna was believed to be a Recent one but probably contains re-worked specimens from nearby Pliocene and Pleistocene outcrops. Sidebottom (1904—1909) described Foraminifera from the shores of the Island of Delos. No work has been done on ecological or distributional lines commensurate with that of Colom (1942), Ruscelli (1949), Giunta (1955) and others in the western area. In order to have some criteria for detecting displaced faunas in the long cores and hence the reliability of the core faunas for establishing geological history of the core sediments, an intensive study was made of the benthonic Foraminifera in the surface sediments. Table 3 gives the distribution of the benthonic species in per cent of total benthonic population with the stations arranged in order of depth, regardless of location. A few stations which contain specimens obviously displaced from shallow water have been listed separately on the right so that the depth distributions will stand out more clearly. All species occurring at frequencies lower than 0.2 % have been omitted. In addition, all species occurring only rarely, unless they are common in the long cores, are omitted. The resulting fauna, therefore, represents only a part of the species occurring in the area although it forms the major part of the foraminiferal population. Most of the omitted species are from relatively shallow water and, in some cases, have been listed in generic or family groups where such groups appear to have ecological significance. These include Peneroplidae, Miliolodae, *Rosalina* spp., and *Elphidium* spp.

Depth distribution. Five faunal depth assemblages can be defined in the area. More detailed sampling in the open-sea region shoaler than 200 m. might add to this number. The boundaries between these assemblages occur between the Piraeus Harbor station and the first open-sea station at 51 m., at 143—205 m., at 500—700 m., and at 1000—1300 m. Many distributional changes occur between these depths but there are more at these boundaries which give the assemblages within them a relatively uniform character.

Depth Assemblage 1.

This assemblage is represented at only one station located in the harbor at Piraeus. The temperature limits are *ca.* 11—21° C at 25 m. and the salinity *ca.* 39 $^0/_{00}$. The depth of the station is unknown but it is believed to be shallower than 25 m.

The representatives of the Family Peneroplidae are confined to this assemblage. The following species also occur although they are found deeper also:

Asterigerinata mamilla
Cibicides lobatulus
Elphidium advena
E. complanatum
E. crispum
E. cf. *E. minimum*
Miliolidae — many species
Miliolinella circularis
Neoconorbina terquemi
Planorbulina mediterranensis
Reussella spinosissima
Rosalina globularis bradyi
R. obtusa
Rotalia granulata

Spiroloculina grata
Streblus beccarii and variants
Textularia calva

The most abundant species in this assemblage are:

Asterigerinata mamilla (4 %)
Cibicides lobatulus (5 %)
Elphidium crispum and variants (6 %)
Miliolidae species (40 %)
Peneroplidae (6 %)
Planorbulina mediterranensis (13 %)
Rosalina obtusa (7 %)

The assemblage shows many similarites to the »*Posidonia caulini*» fauna of Colom (1942) which occurs shallower than 32 m. in the Bay of Palma, Majorca.

Depth Assemblage 2. 51 m. ± to 143—205 m.

The shallow limit of Assemblage 2 is represented here by the station at 51 m. and may in reality occur shallower. The temperature limits are about 12—20° C at 50 m., and 13—16° C at 200 m. The salinities are in most cases 38—39 $^0/_{00}$.

The following species are confined to this assemblage:

Astrononion stelligerum
Bolivina subaenariensis (rare)
Bulimina aculeata (1 sta. only — in the cores it is sometimes common with no evidence of displacement from shallow water)
Elphidium granosum
E. pulvereum
Gypsina vesicularis
Neoconorbina williamsoni (occurs rarely — probably more widespread in depth distribution)
Nonion sp. B
Parrellina verriculatum
Rosalina spp.
Spirillina wrightii
Stomatorbina concentrica

The following additional species have their shallow depth limit between 50—82 m.:

Bigenerina nodosaria
Bolivina attica
B. catanensis
Bulimina costata
B. gibba
B. marginata
Cassidulina carinata
C. cf. *C. oblonga*
Eponides repandus
Gavelinopsis praegeri
Hanzawaia rhodiensis
Höglundina elegans
Lagenonodosaria scalaris
Nonion barleeanum, etc.
Nonionella turgida
Pullenia quinqueloba
Pyrgo anomala
Pyrgoella sphaera (1 sta. only)
Quinqueloculina aff. *Q. lamarckiana*
Robulus spp.
Rosalina aff. *R. columbiensis*
Sigmoilina distorta
Siphotextularia concava
Sphaeroidina bulloides
Spirillina vivipara
Spiroloculina angulosa
S. canaliculata
Textularia conica
T. sagittula
Uvigerina mediterranea
Valvulineria complanata

The following species have their shallow depth limit between 104—177 m.:

Biloculinella labiata
Bolivina difformis
B. dilitata dilitatissima
B. pseudoplicata
Cassidulina crassa
Cibicides aff. *C. floridanus*
Glomospira charoides
Gyroidina cf. *G. neosoldanii*
G. umbonata

Hyalinea balthica
Planulina ariminensis
Pseudoclavulina crustuta
Siphonina reticulata

The following species do not occur deeper than 143—205 m. and are, therefore, confined to Assemblages 1 and 2:

Astrononion stelligerum
Elphidium advena
E. complanatum
E. crispum
E. cf. *E. minimum*
Reussella spinosissima
Rosalina globularis bradyi
Rotalia granulata
Streblus beccarii and variants

The species which make up the greater part of the faunal population in Assemblage 2 are as follows:

Asterigerinata mamilla (up to 13 %)
Bolivina catanensis (up to 8 %, continues deeper)
Cassidulina carinata (up to 14 %)
C. cf. *C. oblonga* (up to 9 %)
Cibicides lobatulus (up to 15 %)
Elphidium complanatum (up to 7 %)
E. crispum (up to 7 %)
Hanzawaia rhodiensis (up to 7 %)
Miliolidae (up to 14 %)
Neoconorbina terquemi (up to 7 %)
Textularia sagittula (up to 9 %)

Depth Assemblage 3. 143—205 m. to 500—700 m.

The temperature limits are 13—16° C at 200—300 m., 14—15° C at 400 m.; at 500 m. there is a fairly stable temperature of *ca.* 14° C. The salinities are about 38—39 ‰.

The species confined to Assemblage 3 are:

Angulogerina angulosa
Globobulimina subspinescens (500—600 m.; also listed in Assemblage 4)
Loxostomum alatum

The following species have their shallow depth limit between 143—205 m.:

Cassidulina subglobosa
Gyroidina altiformis
Involutina cf. *I. planorbis*
Robertina translucens
Sigmoilina schlumbergeri
S. tenuis
Spirophthalmidium acutimargo
Uvigerina auberiana

The following species do not occur deeper than 500—700 m.:

Angulogerina angulosa
Bolivina attica
B. catanensis
B. difformis
Bulimina gibba
Eponides repandus
Nonion sp. B
Nonionella turgida
Planorbulina mediterranensis
Pyrgo anomala
Rosalina aff. *R. columbiensis* (1 exception)
R. suezensis
Siphotextularia concava
Spiroloculina angulosa (1 exception)
Textularia calva
T. conica
T. sagittula

The following species, which in most cases have their highest frequencies in Assemblage 3, form the greater part of the population:

Bolivina catanensis (up to 8 %, also common shallower)
Bulimina costata (up to 16 %)
B. marginata (up to 13 %)
Cassidulina crassa (up to 7 %)
Cibicides aff. *C. floridanus* (up to 10 %)
Gyroidina altiformis (up to 15 %, also common deeper)
Nonion barleeanum, etc. (up to 24 %, also common deeper)
Planulina ariminensis (up to 5 %)

Uvigerina mediterranea (up to 37 %, also common deeper)

Depth Assemblage 4. 500—700 to 100—1300 m.

The temperatures at these depths are 13—14° C and the salinities slightly less than 39 ‰. Depth Assemblage 4 occurs chiefly in the transitional zone between intermediate water and deep water defined by Pollak (1951).

The species apparently confined to this assemblage are:

Bolivina albatrossi
Chilostomella mediterranensis
Cibicides wuellerstorfi (1 sta. only)
Globobulimina pseudospinescens (500—600 m., also listed in Assemblage 3)
Lenticulina peregrina
Patellina corrugata
Rotamorphina ? involuta

The following additional species have their shallow depth limit in Assemblage 4:

500—600 m.
Epistominella rugosa convexa
Glomospira cf. *G. gordialis*
600—700 m.
Articulina tubulosa and variants
1000—1300 m.
Cibicides wuellertorfi

The following species do not occur deeper than 700—800 m.:

Bigenerina nodosaria
Hyalinea balthica
Neoconorbina terquemi
Pseudoclavulina crustata
Sigmoilina distorta
Uvigerina auberiana
Valvulineria complanata

The following species do not occur deeper than 800—1000 m.:

Cassidulina carinata
C. cf. *C. oblonga*
Lagenonodosaria scalaris
Spirillina vivipara
Spiroloculina grata

The following species do not occur deeper than 1000—1300 m.:

Biloculinella labiata
Bolivina dilitata dilitatissima
Bulimina marginata
Cassidulina crassa
C. subglobosa
Cibicides lobatulus
Gavelinopsis praegeri
Gyroidina umbonata
Hanzawaia rhodiensis
Höglundina elegans
Planulina ariminensis
Pullenia quinqueloba
Quinqueloculina aff. *Q. lamarckiana*
Robulus spp.
Sigmoilina schlumbergeri
S. tenuis
Siphonina reticulata
Sphaeroidina bulloides
Spiroloculina canaliculata
Spirophthalmidium acutimargo
Uvigerina peregrina (1 sta. only)

The following species occur at high frequencies and make up a large part of the population of Assemblage 4:

Bolivina dilitata dilitatissima (up to 6 %, scattered)
Glomospira charoides (up to 20 %)
G. cf. *G. gordialis* (up to 10 %)
Gyroidina altiformis (up to 34 %)
G. cf. *G. neosoldanii* (up to 67 %)
Höglundina elegans (16 % at 1016 m.)
Involutina cf. *I planorbis* (up to 7 %)
Nonion barleeanum, etc. (up to 42 %)
Uvigerina mediterranea (up to 48 %

Depth Assemblage 5. 1000—1300 to 3974+ m.

There are no stations from 1378 m. to 1788 m. but the assemblage established between 1000 and 1300 m. shows no marked changes shallower than 2358 m. and therefore it is belived that no important change occurs within the unrepresented depths. This assemblage lies in the deep water zone of Pollak (1951). The temperatures are 13—14° C and salinities 38—39 ‰. The fauna is make up of about twenty-two species (excluding a few species listed as »miscellaneous spp.«). The occurrence of these is very irregular and some samples contain only one or two of them. In addition, species may be very common at one station and entirely absent in adjacent (by depth) ones. Similar scattered occurrences are found in the core samples which theoretically should contain species of this depth assemblage. The species with the highest frequencies and most consistent occurrences are:

Glomospira charoides (up to 100 %)
Gyroidina altiformis (up to 23 % shallower than 2738 m.)
G. cf. *G. neosoldanii* (up to 82 % shallower than 2760 m.)
Uvigerina mediterranea (up to 25 %)

The following species occur spasmodically at high frequencies:

Articulina tubulosa and variants
Bulimina costata
Cibicides aff. *C. floridanus*
Glomospira cf. *G. gordialis*
Involutina cf. *I. planorbis*
Nonion barleeanum, etc.
Virgulina complanata
V. mexicana

Discussion.

The similarity of the fauna at the Piraeus Harbor station to that of the Bay of Palma shallower than 30 m., described by Colom (1942), has already been mentioned. The deeper fauna, from 40—50 m., in the Bay of Palma characterized by high frequencies of Textulariidae has no exact analogy in the eastern Mediterranean samples studied. The faunas at 50 m. and 500 m. in the Ligurian Sea studied by Ruscelli (1949) are analogous to eastern Mediterranean faunas at these depths. Similarly the faunas at 57 m. and 135 m. studied by Giunta (1955) are similar in many ways to those of Assemblage 2 although there are some differences such as higher frequency occurrences of *Bulimina aculeata* and *Valvulineria bradyana* (Fornasini) (probably the species here identified as *V. complanata*). Table 4 gives some comparisons of the depth assemblages established here with those of other areas. When the assemblage boundary depths given are not sharp (i. e. 50—100 m.) an average is given (i. e. 75 m.) for simplification.

The species characteristic of these are not necessarily the same but in most cases they are similar. In the eastern Mediterranean surface sediment samples some forms do not range as deeply as they do elsewhere. These species, however, occur in core samples which show no evidence of the presence of displaced material. This points to the possibility that the sampling of the deeper surface sediments in this area is not completely representative. Some of these species are:

Bolivina albatrossi
B. catanensis
B. dilitata dilitatissima (Medit. only)
Bulimina marginata
Cassidulina carinata
C. crassa
C. cf. C. oblonga
Chilostomella mediterranensis (Medit. only)
Gavelinopsis praegeri
Globobulimina pseudospinescens
Loxostomum alatum
Pyrgo anomala
Quinqueloculina aff. *Q. lamarckiana*
Sigmoilina tenuis
Spiroloculina canaliculata
Spirophthalmidium acutimargo
Valvulineria complanata

Table 4 shows that eastern Mediterranean depth assemblages follow a pattern similar to those of other areas. Assemblage 2 (51 to 143—

TABLE 4. Comparative depth assemblages in various areas (depths are in meters).

	I	II		III		IV	V	
E. Mediterranean	Bay	50(?)–174		174–600		600–1150	1150–3974+	
W. Coast of Africa (Colom, 1950)	9–51	53–323		–		623–878	–	
Coast of Galicia (Colom, 1952)	–	15–250		250–450	450–655+	–	–	
E. Coast of U. S. (Parker, 1948)	0–15	15–90	90–300	300–680		–	–	
(Phleger, 1942)	–	–	–	200–500		500–1000	1000–1500	1500–3000+
Gulf of Mexico NW (Phleger, 1951) ..	–	18?–100	100–200	200–625		625–1150	1150–1900	1900–3000+
NE (Parker, 1954) ...	–	12?–90	90–140 140–200	200–425		425–950	950–3000+	
W. Coast of U. S. (Natland, 1933)	Lagoon (0.3–2)	4–38	38–274	274–1981			1981–2441+	

205 m.) coincides approximately with the isothermal seasonal layer; Assemblage 3 (143—205 to 500—700 m.) coincides with the main thermocline or intermediate-water layer; Assemblage 4 (500—700 to 1000—1300 m.) coincides approximately with the transition zone between intermediate and deep water (*vide* Pollak, 1951); Assemblage 5 (deeper than 1000—1300 m.) coincides approximately with the deep-water layer (*vide* Pollak, 1951). The water of these various layers has different properties and is derived from different sources. The key differences affecting the Foraminifera are unknown although temperature is generally believed to be one of the most important in open-sea environments.

Non-depositional areas. At some stations the specimens are badly preserved and frequently filled with glauconite. This suggests that deposition at these localities is slow and the faunas are, therefore, not necessarily modern. Such conditions are found to a marked degree at stas. 4657 A, 4652, B. S. 61, 4718, 4703, 4702, and 4671. The faunas, both planktonic and benthonic, however, appear to be analogous to the modern ones.

Displaced faunas. Seven samples containing a significant number of displaced specimens are listed separately in Table 3. Additional samples may contain a few displaced specimens. Examples are the occurrences of *Reussella spinosissima* and *Sigmoilina distorta* at Sta. 4711. Displacements can be easily detected when known shallow species are moved into deep water. When a deep-water sample is seen to contain several of these it is suspect and all occurrences should be distrusted. When short range displacement occurs it is difficult to detect and there may be many more such displacements than are realized.

The seven stations showing a large amount of displacement (*vide* Table 3) are B. S. 61, 4703, 4659, 4675, 4655, 4691, and 4665, ranging in depth from 462 m. to 1587 m. All these are in moderately deep water very close to the coast: Sta. 4691 near Israel, Sta. 4703 near Libya, Stas. 4675 and B. S. 61 near Crete, Stas. 4655 and 4659 near Turkey, and Sta.

4665 near the Island of Samothrace. At these localities there must be relatively steep gradients from shallow to deep water and, therefore, they are ideal places for displacement by slumping or turbidity currents. These samples also contain species which are normal for their depths.

Foraminifera in Cores

The distributions of the planktonic and benthonic populations in the cores are given in Tables 6—20 (*vide* Appendix A). The planktonic species are recorded on a percentage basis, the benthonic in numbers of specimens present. The benthonic populations are usually small and percentage calculations are invalid. In general, data are given for each 50 cm. of depth in the core unless changes occur at shorter intervals. The total abundance of planktonic specimens larger than 0.149 mm. diameter has been estimated for each sample. These estimates do not necessarily reflect the ratio of calcium carbonate present since many samples contain very large populations of relatively small specimens, even within the limits studied.

Benthonic Foraminifera

Systematic discussions of the benthonic species and data on their occurrence in the cores are given in Appendix B. The benthonic populations are very small relative to the planktonic, the largest populations usually being found in the core sections believed to reflect colder climates. In most of the cores, samples containing more than one hundred benthonic specimens are the exception and usually the number is far less but Cores 184 and 192—194 consistently contain more specimens than the other cores. Core 184 was taken at the shallowest station, 1176 m., and, therefore, comes within the limits of Depth Assemblage 4 where the abundance of benthonic specimens is greater than in Assemblage 5. Cores 192—194 contain many specimens apparently displaced from shallow depths. Such samples usually have larger benthonic populations, an extreme case being sample 73 in Core 188 which has a population of 1981 specimens.

Occasionally core samples contain »floods» of a single species. Examples are the occurrences of *Bulimina aculeata* in Core 189, sample 77 (1280 specimens) and 85 (896 specimens), and Core 190, sample 91 (768 specimens). The upper occurrence in Core 189 may correlate with that of Core 190. Other examples are the occurrences of *Globobulimina* ? sp. in Core 189, sample 47 (86 specimens), and *Pyrgo serrata* in Core 193, sample 36 (94 specimens). The writer has not previously encountered such single species »floods» in cores and the reason for them is unknown. Miss Ruth Todd (personal communication) postulates a semiplanktonic habit for similar occurrences of *Globobulimina affinis* and *Chilostomella oolina*, in western Mediterranean cores.

The species which occur most consistently and abundantly are: *Articulina tubulosa* (and variants) found deeper than 684 m. in the surface sediments and *Miliolinella circularis* which occurs in the surface sediments at all depths.

Many cores contain specimens which have obviously been derived from shallow sediments. Many other displaced occurrences probably also occur but are difficult to detect. The method used for determining which species are displaced is similar to that described by Phleger, *et al.* (1953, p. 24). Populations containing known shallow species were analyzed. Associated species with somewhat deeper depth ranges found only in such assemblages are also considered to be displaced. Samples containing such species sometimes are also richer in species known to live in a deep habitat, but the reason for this is obscure. The species in the cores believed to be displaced from shallow water are given below, with their depth ranges in the surface sediments.

Asterigerinata mamilla (bay—179 m.)
Astrononion stelligerum (51—143 m.)
Biloculinella labiata (106—1378 m.)
Bolivina attica (82—338 m.)
B. difformis (115—567 m.)
Cibicides lobatulus (bay—1265 m.)
Elphidium advena (bay—179 m.)
E. complanatum (bay—205 m.)
E. crispum (bay—338 m.)
E. granosum (51—201 m.)
E. cf. *E. minimum* (bay—179 m.)
E. pulvereum (106—201 m.)
E. spp.
Gyroidina umbonata (205—1016 m.)
Hanzawaia rhodiensis (51—1378 m.)
Lagenonodosaria scalaris (82—996 m.)
Lenticulina peregrina (567—1016 m.)
Nonion sp. A (not observed in surface sediments)
N. sp. B (51—567 m.)
Nonionella turgida (86—567 m.)
Parrellina verriculata (51—201 m.)
Planorbulina mediterranensis (bay—256 m.)
Planulina ariminensis (106—1016 m.)
Pullenia quinqueloba (82—1265 m.)
Reussella spinosissima (bay-117 m.)
Rosalina aff. *R. columbiensis* (51—201 m.)
R. globularis bradyi (bay—143 m.)
R. obtusa (bay—996 m.)
R. suezensis (71—256 m.)
R. spp.
Rotalia granulata (bay—143 m.)
Rotamorphina ? involuta (567—996 m.)
Sigmoilina distorta (51—731 m.)
S. schlumbergeri (179—1016 m.)
Siphonina reticulata (104—1016 m.)
Siphotextularia concava (51—631 m.)
Sphaeroidina bulloides (75—1265 m.)
Spirillina vivipara (71—996 m.)
S. wrightii (75—143 m.)
Spiroloculina angulosa (71—541, 1016 m.)
S. grata (bay—859 m.)
Streblus beccarii and variants (bay—179 m.)
Textularia conica (51—631 m.)
T. sagittula (51—366, 731 m.)
Uvigerina auberiana (179—731, 1265 m.)

The following are questionably displaced when found in the cores, since there are some occurrences where displacement cannot be proved:

Angulogerina angulosa (179—731 m.)
Bulimina gibba (71—658 m.)
Hyalinea balthica (106—799 m.)
Neoconorbina terquemi (bay—799 m.)
N. williamsoni (117—179 m.)
Nonion barleeanum, etc. (51—1265, 1844 m.)
Wiesnerella auriculata (not observed in surface sediments)

The cores having the greatest abundance of displaced specimens are, as is to be expected, those nearest shallow coastal areas. Cores 184, 188, 191—196, 198, 199, and 200 contain such specimens to a greater or lesser degree. All of these, except Cores 188 and 198, are relatively near shore at depths greater than 2000 m., in most cases considerably deeper. Cores 188 and 198 have less displaced material than the others. In Core 188 only one sample (709.5 cm.) contains such material and in Core 198 two (97.5 cm. and 899.5 cm.) with a questionable third zone at the top. Cores 186, 187, 189, 190, and 197 are relatively free of detectable displaced material although very occasional shallow-water specimens are found. There is some evidence, however, in Core 186 of displacement of deeper species which in other cores only occur in association with shallow species but here do not.

Planktonic Foraminifera

Most planktonic specimens in the cores are well preserved, with only occasional samples showing advanced solution of the calcium carbonate tests although many samples contain a few broken specimens. Frequent samples contain few or no planktonic specimens but this

(338)

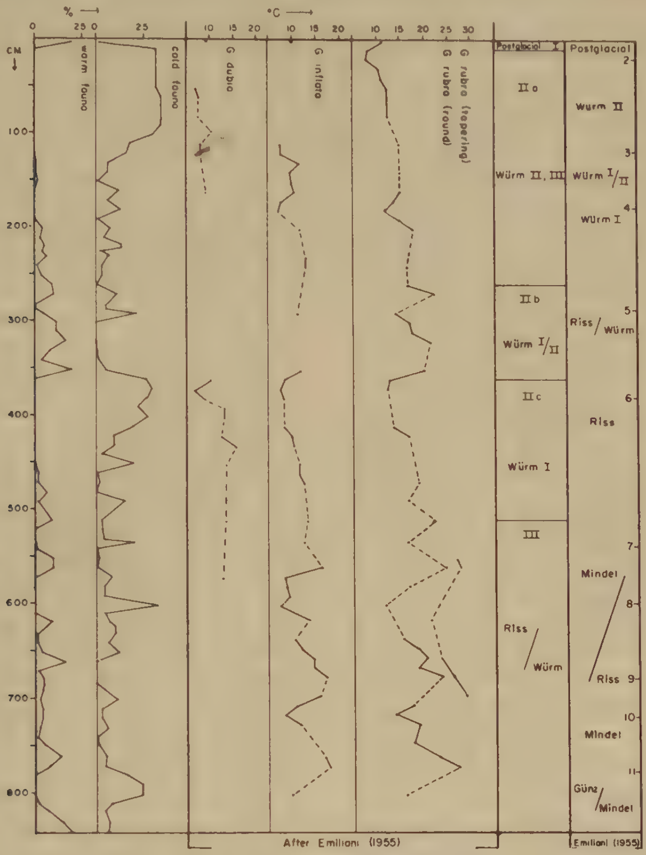

Figure 2. Frequency curves and interpretation of »warm» and »cold» planktonic species-groups in Core 189 compared to Emiliani's (1955) temperature curves based on isotopic data and his interpretation.

scarcity is thought to be due to dilution by relatively rapid sedimentation rather than to removal by solution.

The planktonic species found in the cores are the same as those in the surface sediments with the exception of one occurrence of *Globorotalia punctulata* at a depth of 609.5 cm. in Core 197.

Schott (1935) and Ericson and Wollin (1956 b) have demonstrated that *Globorotalia menardii* (d'Orbigny) is an excellent indicator of the sections in North Atlantic cores deposited in relatively warm intervals and hence that the presence or absence of this species shows the sequence of warm and cold time intervals reflected by the core sediments. Similarly Cushman (1941), Kane (1953), Ovey (in Wiseman and Ovey, 1950), Phleger *et al.* (1953), and others have evaluated various other species as temperature or water mass indicators in the North Atlantic and elsewhere. In the eastern Mediterranean the problem of detecting how planktonic species respond to temperature changes is complicated by the fact that some species appear to be influenced sometimes by other factors. They do not act in rhythm

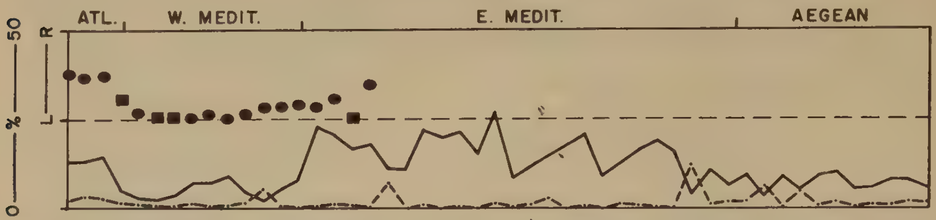

Figure 3. Frequencies of »warm» (solid line) and »cold» (dotted line) planktonic species-groups and coiling directions of *Globorotalia truncatulinoides* in surface sediment samples of the Mediterranean and Aegean seas and the adjacent North Atlantic (● based on more than 100 specimens ■ 30—100).

with others of similar postulated temperature requirements or, conversely, to those of opposite preference. A few species, however, which previous work has shown prefer cold water environments appear to fluctuate in unison and in opposition to a few species preferring warm water environments. The various publications just mentioned provided these data. Some known to favor a warm water environment elsewhere do not occur in the Mediterranean. *Globorotalia menardii* and *Pulleniatina obliquiloculata*, two of the most reliable warm water indicators in the North Atlantic and Gulf of Mexico, are examples. Their absence in even the »warmest» core faunas has been postulated in a previous section as due to the indigenous character of the Mediterranean faunas resulting from the presence of an effective barrier to the invasion of North Atlantic species.

The most reliable indicators of cooler water environments in the cores are *Globigerina pachyderma* and *Globorotalia scitula*; those of warmer environments are *Globigerinella aequilateralis*, *Globigerinoides rubra* s. s., *G. sacculifera* and *Hastigerina pelagica*. Figure 2 gives the frequency curves of these two faunal groups in Core 189, Figure 6 for all the cores (except Core 200). Since the population counts of »*G. rubra*, etc.» (*vide* Tables 6—20) contain several species (*vide G. rubra* in Appendix B) 10 % of »*G. rubra*, etc.» has been added to the »warm» faunal group frequencies when *G. rubra* s. s. is present; this figure may be too high in some cases and too low in others. Since the species appears to be present only during the warmest periods this a mount acts an added »bonus» to the »warm» fauna frequency for the indication of such intervals. Figure 2 also gives the isotopic temperature curves for Core 189 published by Emiliani (1955 b). The agreement of these with the frequency curves of the »cold» and »warm» faunas is striking. Figure 3 gives frequency curves for these same faunas in the surface sediment samples for comparison.

Figures 4 and 5 give the frequency curves of all the planktonic species in Cores 189 and 190. A study of these shows that additional species fluctuate more or less in unison with those of the »warm» and »cold» faunas but they are not included because of the lack of published data on their distribution. The species whose frequency curves agree with those of *Globigerina pachyderma* and *Globorotalia scitula* are *Globigerina quinqueloba* and, to a somewhat less extent, *Globigerinita glutinata*. *Globigerina bulloides* sometimes fluctuates similarly but often independently. This may be due to the inclusion of more than one species in the population counts of this form. The frequency curve of *G. inflata* agrees to a great extent but also shows anomalous fluctuations. The frequency curve of »*Globigerinoides rubra*, etc.» agrees approximately with those of the species of the »warm» group but some of the

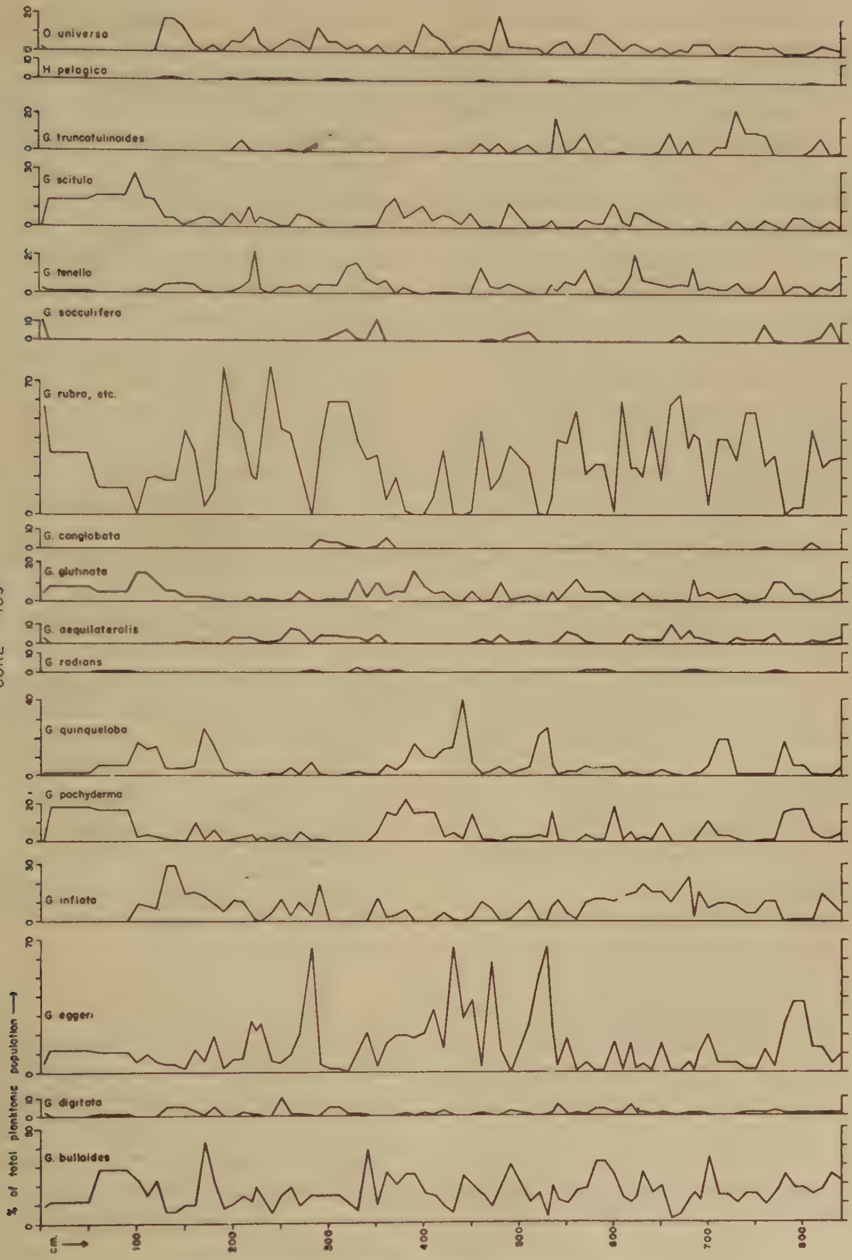

Figure 4. Frequency curves of planktonic species in Core 189.

species included in this category (*vide G. rubra* in Appendix B) may behave differently.

The frequency curve of *Globigerina eggeri*, as previously shown by Kullenberg (1952, »*G. dubia*»), fluctuates in a very individual manner. In some samples this species forms over 50 % of the planktonic population. No firm correlations can be made between cores of these high frequency occurrences although they appear to be in the same general sections. The high frequency of *G. eggeri* in a sample causes a relative scarcity of the diagnostic species but apparently such occurrences are found in sections reflecting both cold and warm intervals.

In general, the core faunas show the presence of two long, cold intervals separated by a short warm one and preceded (in time) by a long warm interval showing one or two cold oscillations which are relatively very short. It is probable that a portion of the top section is missing in most of the cores (Kullenberg, 1955). This loss appears to be relatively small in most cases, probably not exceeding one meter and usually less. All but Core 190 show a short period of warming at the top similar to that shown in North Atlantic cores by various authors (Ericson and Wollin, 1956 a, b; Phleger *et al.*, 1953, etc.). The fauna at the top of Core 190 apparently reflects the uppermost cold interval.

Figure 6 also gives data on the coiling direction of *Globorotalia truncatulinoides*. The coiling directions of various other species were investigated in Core 187 but no significant changes occurred. These species showed the following coiling directions throughout the core;: *Globigerina eggeri* 99—100 % right coiling *G. inflata* 96—100 % left coiling, *Globorotalia scitula* 97—100 % right coiling. In all cases the coiling direction is given for 100 specimens except for *G. scitula* where 50 specimens are used. The coiling direction of *Globorotalia truncatulinoides* shows many fluctuations in the cores. Unfortunately this species is frequently absent so that continuous curves cannot be made. The species is almost entirely absent in the eastern Mediterranean surface sediments but in the western area the coiling direction shifts from 79 % left coiling near Gibraltar to 99 % at about Longitude 0°. High ratios of left coiling (88 %+) are maintained eastward to Sta. 4711 where 62 % is found (Parker, 1955). Eastward from this station there are too few specimens for analysis. The core data suggest that the left-coiling province indicated in the western area is maintained in the eastern since samples at, or near, the »tops» contain specimens indicating left-coiling dominance. Starting at the top of the cores, left coiling is dominant until a point just above the cold faunal optimum of the uppermost cold interval where there is a shift to right-coiling dominance. Ericson, Wollin, and Wollin (1954) made similar observations in North Atlantic cores taken where left coiling of *Globorotalia truncatulinoides* is dominant in modern faunas. Below this shift to right coiling in eastern Mediterranean cores occurrences of the species are sparse almost to the bottom of the lower long cold period but show several coiling-direction fluctuations. In the lower part of this cold period and in the long warm interval below occurrences are much more frequent and show many fluctuations. These occur often but by no means invariably at the same times as faunal shifts probably caused by climatic changes.

Discussion

In the cores the planktonic faunas reflecting changing climates show changes from what may be called the modern cool-temperate fauna (*vide* Parker, 1955) to a cooler one indicative of glacial times and, in some cases, to a warmer one indicative of warmer-than-present-day climates. Emiliani (1955 b) gives temperature ranges from 7.9—27° C calculated from oxygen isotope analyses of »*Globigerinoides rubra* (rounded form)» in Core 189. Analyses of other species in the core give simultaneously

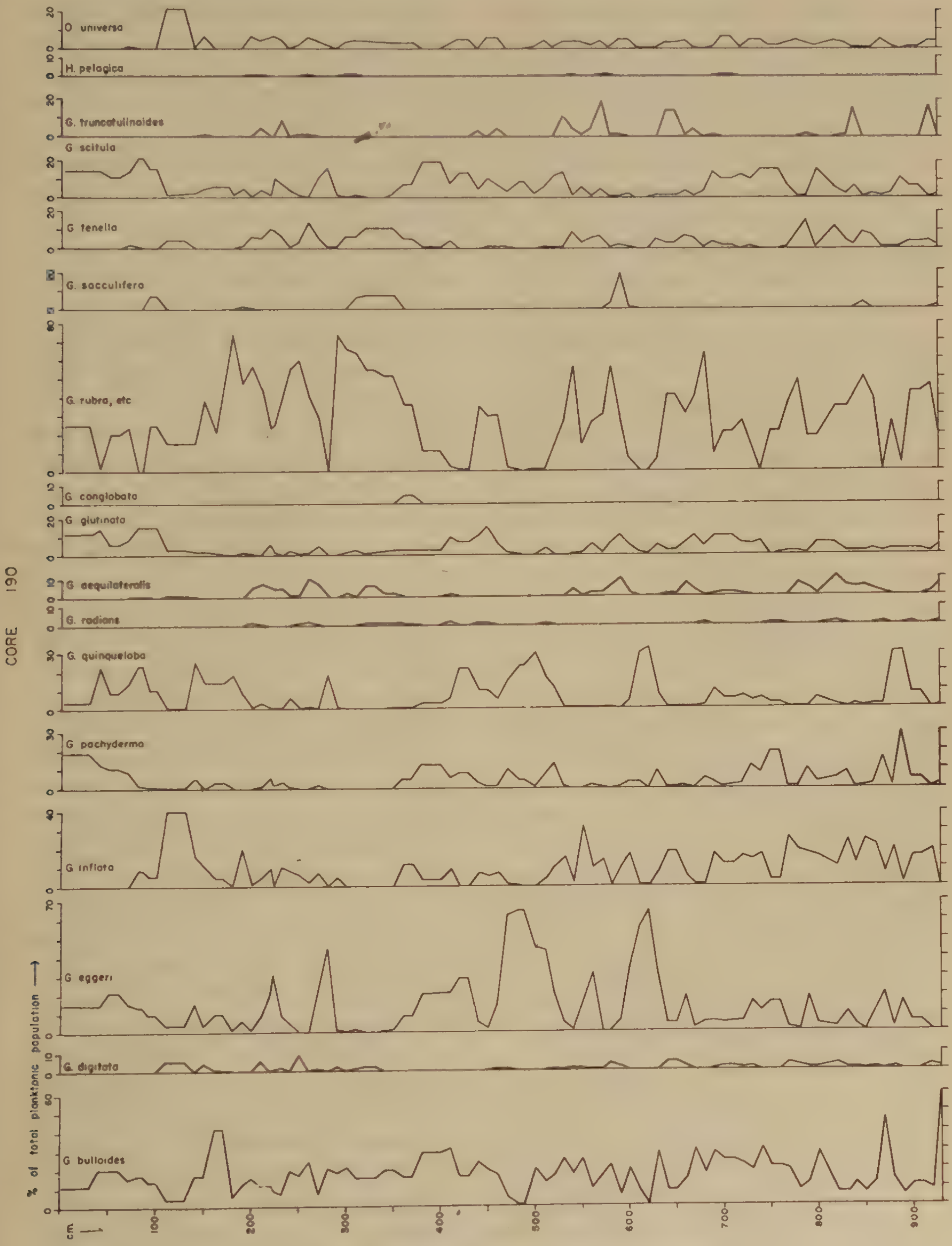

Figure 5. Frequency curves of planktonic species in Core 190.

different results although they show the same fluctuations. The maximum temperature calculated (»*G. rubra* (tapered form)») was 32.8° C, the minimum (»*Globigerina dubia*») 6.9° C. Emiliani postulates that *G. rubra* (rounded and tapered), which indicates the highest temperatures, secretes its calcium carbonate test near the surface where temperatures are expected to be higher as opposed to the deeper habit of other species indicating simultaneously lower temperatures. In addition, he says that in a sea like the Mediterranean where seasonal variation of temperature occurs »the isotopic temperatures commonly represent values close to the summer mean, because summer is apparently the season during which most of the carbonate deposition takes place.» (*op. cit.*, p. 88). This supposition seems rather odd in view of the 7.9—27.0° C range calculated for the rounded form of »*G. rubra*». In modern times high temperatures analogous to his maximum calculated temperature of 32.8° C are found in the Persian Gulf, but this is a shallow sea whose average depth is only 25 m., maximum depth 90 m. (Sverdrup, Johnson, and Fleming, 1942). A mean summer temperature of this magnitude for the surface layer at localities similar to those from which the cores were taken would reflect far warmer conditions than any to be found in modern times, even in the warmest regions, in oceans of comparable depths. Zooxanthellae are known to exchange oxygen with calcium-carbonate-forming organisms (Emiliani, 1955 a, p. 544). That Zooxanthellae or »yellow cells» occur in foraminiferal tests has been reported by Murray (1897) in *Globigerina bulloides* and *Globigerinella aequilateralis* and by Rhumbler (1900) in *Orbulina* and *Globigerina*, specifically *G. bulloides*. It is very likely that they are to be found in other planktonic species as well. For this reason, and in view of the unusually high temperatures registered by »*G. rubra*», temperatures calculated from oxygen isotope analyses of planktonic Foraminifera should be viewed with caution. As mentioned previously, the temperature fluctuations registered by these isotopic temperature studies are in agreement with those shown by the planktonic population studies.

Emiliani (1955 b) suggests a time sequence for Core 189 which extends back to the Gunz/Mindel interglacial period, giving an approximate date for the level at 720 cm., which he correlates with the Mindel glaciation, of 200000 years B. P. This figure is much lower than that of workers such as Kay (1931), Zeuner (1952), Penck and Bruckner (1909), Ericson and Wollin (1956 b) and others for the same event. It is believed that a more realistic picture can be obtained by placing the beginning of the Last Glaciation at the 510 cm. level (approximate) in Core 189. The cold oscillation from 569.5—649.5 cm. would then represent that of the Last Interglacial (*vide* Zeuner, 1952) and the temperature minimum at 790—800 cm. might possibly represent the final part of the Penultimate Glaciation although it is of comparatively short duration and might represent another cold oscillation of the interglacial period. Both of these oscillations are much shorter than the two long cold intervals which occur in the upper part of the core and, therefore, do not appear to be of sufficient duration to represent glacial periods of the magnitude of the Riss or Mindel. On the other hand, if both the upper cold intervals were considered to represent glacial periods (Würm and Riss) the long warm interval below is proportionally much too long to represent a normal interglacial period (Riss/Mindel) in view of the much smaller length of the warm interval between the upper cold intervals. A comparison of the postulated time scale and the numbering system used with those of Emiliani (1955 b) is shown in Figure 2.

Figure 6 gives the correlation between cores of the cold and warm intervals reflected by the faunas, using the interval numbers

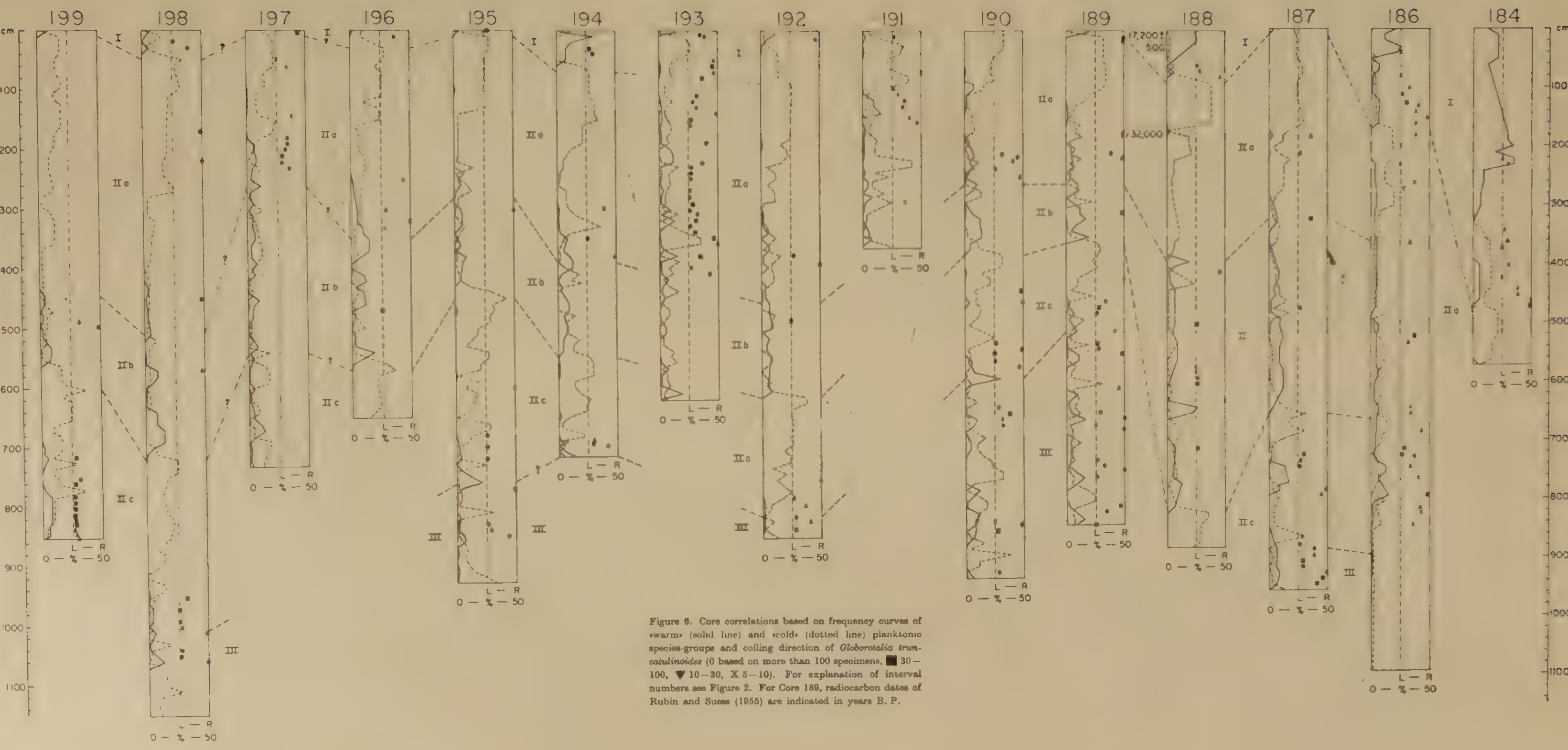

Figure 6. Core correlations based on frequency curves of »warm« (solid line) and »cold« (dotted line) planktonic species-groups and coiling direction of *Globorotalia truncatulinoides* (0 based on more than 100 specimens, ■ 30—100, ▼ 10—30, X 5—10). For explanation of interval numbers see Figure 2. For Core 189, radiocarbon dates of Rubin and Suess (1955) are indicated in years B. P.

shown in Figure 2. These correlations agree in most cases with those made by other workers using other criteria. Between Cores 189 and 190 Kullenberg (1952) makes correlations based on various sediment bands which confirm those made here. His correlations based on the planktonic foraminiferal faunas are also in agreement although his interpretations of the faunas differ somewhat. Mellis (1954) has correlated two sets of ash bands in various cores. These, too, confirm the present ones with the exception of the upper ash bands in Cores 187 (39—40.5 cm.) and 188 (146.5—151 cm.). In the present study these bands appear to correlate but do not correlate with the upper bands in Cores 189 (0—2 cm.) and 192 (0—4 cm.), which are also apparently correlative in the present scheme. In Cores 187 and 188 the upper bands are very close to the lower ones, both being in the upper cold interval. In Cores 189 and 192 they are near the top, widely separated from the lower ones, and occur above the cold interval in what is interpreted to be postglacial time.

The planktonic faunas at 219.5 cm. in Core 184 and 29.5 cm. in Core 186 appear to reflect a climate warmer than that of the present day with frequencies for the »warm» fauna of 25—35.5 % as opposed to modern ones of mostly less than 20 % (*vide* Figures 3, 6). It is suggested that these faunas may reflect the so-called »Climatic Optimum» of *ca.* 5000 years B. P. (Flint, 1947, and others). There is slight evidence of similar conditions at 9.5 cm. in Core 194 and at the top of Core 188. These ultra-warm faunas correlate and their relative positions in Cores 184 and 186 are reasonable in view of the positions of the core stations in respect to the Nile Delta. Core 184 shows a far longer section reflecting postglacial warming than does Core 186 as is to be expected since it was taken nearer the delta.

Faunal evidence suggests that the final maximum of the Last Glaciation is reflected at 479.5 cm. in Core 184 and 169.5 cm. in Core 186. This evidence lies not only in the high frequency of the »cold» fauna but also in the fact that these sections precede (geologically) by a evry short distance the shift from right- to left-coiling dominance of *Globorotalia truncatulinoides* believed to have taken place soon after the Last Glaciation, as has been previously discussed. In Core 189 the position of this maximum appears to be at 10 cm. The section from 10—20 cm. is that for which Rubin and Suess (1955) give a radiocarbon date of17200 ± 500 years B. P. Assuming that this point can be correlated with that at 479.5—489.5 cm. in Core 184, a sedimentation rate can be calculated for the section from 219.5 cm. to 490 cm. This rate is 22.1 cm./1000 years which seems a reasonable one. Making the same assumption for the section at 169.5—179.5 cm. in Core 186, the sedimentation rate for this core between 29.5 cm. and 179.5 cm. is 12.2 cm./1000 years. We hope to check these dates by radiocarbon dating of material from these cores in the near future.

A similar series of calculations for Core 194 gives a sedimentation rate of 5.7 cm./1000 years. Extrapolating this rate to the bottom of the core, postulated to reflect a time close to the beginning of the Würm glaciation, we obtain a date for that event of 130000 years B. P., which is a rather large figure. The presence of displaced material in this core, however, suggests that a uniform sedimentation rate cannot be assumed. Further evidence of this is the frequent alternation of samples containing few or no planktonic Foraminifera with those containing large numbers. The assumption of uniform sedimentation in such a relatively small sea seems very dangerous but if it is understood that the calculated rates are high speculative they may be suggestive.

If we assume a date of 80000 years B. P. for the beginning of the Last Glaciation and 40000 years B. P. for the beginning of the final part (Würm II, III) of the Last Glaciation (Suess, 1956) additional sedimentation rates

TABLE 5. Estimated sedimentation rates in cm./1000 years.

Core no.	199	198	197	196	195	194	192	189*	188	187	186	184
Years B. P. 5000[1])—17200±500[2])						5.7			6.7		12.2	22.1
5000—40000[3])						10.8			11.1		9.4	
5000—80000[4])											11.4	
17200—40000	18.6	19.7	10.5	13.5	11.4	13.8	15.7	10.5	12.8	13.1	7.9	
17200—80000		15.1			10.7		11.3	8.6		13.5	11.3	

may be calculated using the geological interpretation of the cores made on the basis of the planktonic faunas (*vide* Figures 2, 6). Table 5 gives these for some of the cores. The rates are highest for Cores 184, 198, and 199 and lowest for Cores 189 and 197.

Appendix A: Core Descriptions

In the core descriptions the following terminology will be used for the sake of brevity:

»warm fauna» — consists of *Globigerinella aequilateralis, Globigerinoides rubra* s. s. (10 % of *G. rubra*, etc., when present), *G. sacculifera, Hastigerina pelagica*

»cold fauna» — consists of *Globigerina pachyderma* and *Globorotalia scitula*

I — post-glacial warm period to modern times

II a — last phases of the Last Glaciation (Würm II, III) (Stages 2—4 of Emiliani, 1955 b)

II b — interstadial of the Last Glaciation (Würm I/II—III) (Stage 5 of Emiliani, 1955 b)

II c — first phase of the Last Glaciation (Würm I) (Stage 6 of Emiliani, 1955 b)

III — Last Interglacial (Riss/Würm) (Stages 7—11+ of Emiliani, 1955 b)

IV — Penultimate Glaciation (Riss)

The benthonic species listed as single-species occurrences at the end of each core description are omitted from the data tables. The numbers in parentheses following the names indicate the core samples in which the specimens were found.

Core 184

Length sampled 570 cm.; depth 1176 m.; population counts given in Table 6.

The planktonic fauna at the top is comparable to that of the present day. This continues below to 60 cm. From 60—170 cm. there are few Foraminifera consisting mostly of *Globigerinoides rubra*, etc., a probable indication of rapid sedimentation. Below 170 cm. the faunas reflect warmer-than-present-day temperatures reaching a maximum at 219.5—30 cm. where the »Climatic Optimum» of ± 5000 years B. P. is postulated. Below this point the warm fauna decreases with a corresponding increase of the cold fauna to 479.5 cm., the top of Ia. Ia extends to the bottom sample which reflects the beginning of a warm oscillation.

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[*] Rate calculated by Emiliani (1955 b) for Core 189, 4.3 cm./1000 years.

[1] »Climatic Optimum».

[2] Radiocarbon date in Core 189 (10—20 cm. from top).

[3] Estimated time of beginning of Würm II, III glaciation.

[4] Estimated time of beginning of Last Glaciation.

Isolated samples throughout the core in addition to the section from 60—170 cm. contain few or no Foraminifera. *Globorotalia truncatulinoides*, never very common, shows left-coiling dominance down to 459.5 cm. where there is a shift to right-coiling dominance just above the top of Ia. This is maintained to 469.5 cm. below which the species is absent.

Down to 199.5 cm. the benthonic populations are small — less than 60 specimens. Below 210 cm., except at 239.5 cm., they are between 106 and 268 specimens. There is some evidence of the presence of displaced specimens below 279.5 cm., although this is not conclusive. The presence of such species as *Elphidium* spp., *Gyroidina umbonata*, *Pullenia quinqueloba*, and *Spirillina vivipara* is suggestive of displacement but, because of the comparatively shallow depth from which the core was taken, may not be indicative.

The following single-specimen occurrences have been omitted from Table 6: *Eggerella bradyi* (49), *Elphidium advena* (49), *Neoconorbina williamsoni* (49, 54), *Patellina corrugata* (35), *Pullenia* cf. *P. riveroi* (35), *Pyrgo lucernula* (35), *Spiroloculina canaliculata* (29), *Spirophthalmidium acutimargo* (49), and *Streblus beccarii* var. (37).

Core 186

Length sampled 1090 cm.; depth 2025 m.; population counts given in Table 7.

The warm fauna at the top is comparable to that of the modern fauna. This increases to a maximum, after a slight decrease, at 30 cm. where the »Climatic Optimum» is postulated to have occurred. Below this point the warm fauna decreases with a corresponding increase in the cold fauna to a maximum at 169.5 cm. the top of IIa. The cold fauna persists below, with some fluctuations and a general decrease, to 359.5 cm., the top of IIb. IIb extends from 359.5—659.5 cm. with three small warm maxima at 499.5—510 cm., 579.5 cm., and 639.5—50 cm., the top of IIc. IIc shows two cold maxima[1]) at 659.5 cm. and 799.5 cm. and extends to 889.5 cm. III extends below to the bottom. The upper boundary of III is very hypothetical since below this point the warm and cold faunas are not well developed. There are few or no Foraminifera from 769.5—80 cm. and below 950 cm., except at 1050 cm., 1069.5 cm., and 1089.5 cm. Occasional isolated samples, in addition, are barren. Very high frequencies of *Globigerina eggeri* occur at 849.5—70 cm. and 972 cm. *Globorotalia truncatulinoides* shows left-coiling dominance down to 149.5 cm. where right-coiling dominance occurs. Below this point occurrences are few and the frequencies are low but the trend is towards left coiling with minor fluctuations to 679.5 cm. where again right coiling is dominant. Below this point there are several fluctuations and a somewhat stronger occurrence to 839.5 cm. below which the species is absent.

The benthonic Foraminifera are comparatively rare, only once exceeding 100 in a sample. They are especially rare from the top to 50 cm. (1—11 specimens), at 759.5 cm. (4 specimens) and from 849.5 cm. to the bottom (0—6 specimens). Displaced specimens occur at 729.5 cm. and possibly 789.5 cm. as shown by the presence of such species as *Asterigerinata mamilla*, *Hanzawaia rhodiensis*, and *Elphidium* cf. *E. minimum*. Several species with a deeper habitat also appear to be displaced though this cannot be definitely established. Among these are *Bulimina gibba*, *Hyalinea balthica*, and *Nonion barleeanum*.

The following single-specimen occurrences have been omitted from Table 7: *Asterigarinata mamilla* (74), *Bolivina pseudoplicata* (32), *Bulimina gibba* (74), *Elphidium* cf. *E. minimum* (74, 80), *Glomospira charoides* (1), *Loxostomum alatum* (4), *Nonion barleeanum*, etc. (13, 24),

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[1]) The term »cold maximum» is used advisedly since it refers to the maximum frequency of the cold fauna rather than directly to the temperature, although the former is believed to reflect the latter.

Pullenia bulloides (6), *Pyrgoella sphaera* (13), *Sigmoilina tenuis* (60, 73), and *Spirophthalmidium acutimargo* (49).

Core 187

Length sampled 950 cm.; depth 2500 m.; population counts given in Table 8.

The fauna at the top of the core is cooler than the modern one but a trace of the warm fauna is present. At 9.5 cm. the warm fauna has disappeared and the cold fauna increased; the top of IIa is tentatively placed at this point. Below the cold fauna persists, showing two maxima at 149.5 cm. and 219.5 cm., to 319.5 cm., the top of IIb. IIb shows roughly three warm maxima at 319.5 cm., 409.5—23.5 cm., and 577.5 cm. It extends to 649.5 cm. IIc has approximately two cold maxima at 649.5—79.5cm. and 809.5 cm. The top of III is at 879.5 cm. and continues, with one warm maximum at 915.5 cm., to the bottom sample where cooler conditions prevail, probably indicating a cool phase of III. Numerous isolated samples throughout contain few or no Foraminifera. Very high frequencies of *Globigerina eggeri* occur from 800.5—14 cm. *Globorotalia truncatulinoides* is found rarely, showing left-coiling dominance to a depth of 779.5 cm. where right-coiling dominance occurs. Below 869.5 cm. the species is more common and the coiling dominance fluctuates rapidly.

With one exception the benthonic population ranges from 0—50 specimens with the highest populations usually occurring in the colder periods; at 459.5 cm. 91 specimens occur of which 77 are *Articulina tubulosa* and variants. There is slight evidence of the presence of displaced specimens at 449.5 cm. and 479.5 cm. shown by the presence of such species as *Asterigerinata mamilla*, *Nonionella turgida*, and *Rosalina obtusa*.

The following single-specimen occurrences have been omitted from Table 8: *Asterigerinata mamilla* (47), *Bolivina pseudoplicata* (46, 51), *B. subaenariensis* (23), *Cassidulina* cf. *C. oblonga* (38), *Epistominella rugosa convexa* (42, 48), *Gavelinopsis praegeri*, etc. (47), *Glomospira charoides* (18), *Hyalinea balthica* (47), *Nonionella turgida* (51), *Patellina corrugata* (7, 51), *Rosalina obtusa* (51), *Rotamorphina? involuta* (51), and *Virgulina mexicana* (69, 96).

Due to a damaged sieve, a part of the population may have been lost in the following samples: 35, 46, 69, 70, 73, 74, 77.

Core 188

Length sampled 880 cm.; depth 2810 cm.; population counts given in Table 9.

The top sample contains a warm fauna of somewhat higher frequency than the modern one, which increases with depth to a maximum at 9.5—20 cm., the postulated »Climatic Optimum». Below this point the warm fauna decreases and the cold fauna increases, with one minor oscillation, to a maximum at 89.5 cm., the top of IIa. Cold faunas persist to 392 cm., showing three maxima at 89.5—158 cm., 209.5 cm. and 349.5 cm. IIb extends from 392 cm. to 819.5 cm. with three warm maxima at 392 cm., 639.5 cm., and 719.5 cm. IIc extends from 819.5 cm. to the bottom with the cold fauna at high frequencies throughout. Many isolated samples are barren of Foraminifera. More extended barren sections occur from 289.5—340 cm., 469.5—90 cm., 539.5—50 cm., and 779.5—800 cm. In some cases there appears to be marked solution of the calcium carbonate tests, especially at 489.5 cm. and 539.5 cm. *Globigerina eggeri* does not occur at high frequencies. *Globorotalia truncatulinoides* occurs with left-coiling predominance at 59.5—70 cm.; at 79.5 cm. a few specimens occur showing right-coiling dominance. No specimens occur below this point to a depth of 409.5 cm. where right coiling is again dominant. At 499.5 cm. left-coiling dominance occurs and persists with several occurrences to 629.5 cm. where a few specimens show right-coiling dominance. One occurrence at 709.5 cm. shows left-coiling dominance; below this point there are no more specimens. The core does not penetrate the zone of abundant occurrence of *G. truncatulinoides* found in many of the cores in the lower part of IIc and III.

Less than 50 benthonic specimens occur in all samples studied with two exceptions. One sample, at 379.5 cm., contains 153 specimens of which 142 are *Articulina tubulosa* and variants. The second is a displaced fauna containing 1981 specimens. This fauna includes such shallow water species as *Rosalina* aff. *R. columbiensis*, *Streblus beccarii* and variants, and various species of *Elphidium*. In addition, many relatively deep species are abundant. The most common of these are: *Bolivina albatrossi*, *B. dilitata dilitatissima*, *Bulimina costata*, *B. marginata*, and *Hyalinea balthica*. The samples above and below this one (not listed in Table 9) do not contain this fauna. In general, benthonic specimens are more common in the cold periods than the warm ones.

The following single-specimen occurences have been omitted from Table 9: *Bolivina catanensis* (73), *B. subaenariensis* (19), *Bulimina aculeata* (1), *Cibicides* aff. *C. floridanus* (20), *Elphidium complanatum* (73), *E.* cf. *E. minimum* (73), *E. pulvereum* (73), *Globobulimina pseudospinescens* (73), *Neoconorbina williamsoni* (73), *Nonion* sp. B (73), *Nonionella turgida* (73), *Patellina corrugata* (73), *Pullenia* cf. *P. riveroi* (73), *Pyrgoella sphaera* (9), and *Reusella spinosissima* (73).

Core 189

Length sampled 840 cm.; depth 2664 m.; population counts given in Table 10.

The planktonic fauna at the top is comparable to the modern one. The cold fauna increases below to a maximum at 9.5 cm., the top of IIa. The section from 10—20 cm. has been dated by Rubin and Suess (1955), using radiocarbon measurements, at 17200 ± 500 years B. P. The cold faunas of IIa predominate to a depth of 209.5 cm. with two strong and one weak cold maxima at 59.5—90 cm., 159.5—80 cm., and 218 cm. The section from 170—80 cm. was radiocarbon-dated by Rubin and Suess as older than 32000 years B. P. IIb extends from 209.5 cm. to 359.5 cm. with three warm maxima at 259.5 cm., 319.5 cm., and 350.5 cm. The cold faunas of IIc extend from 359.5 cm. to 509.5 cm. with one strong and two minor cold maxima at 369.5—400 cm., 449.5 cm., and 489.5 cm. III extends from 509.5 cm. to the bottom. The cold maximum at 789.5 cm. appears to be of comparatively short duration and probably is a cold oscillation of III although there is a possibility that it may be the final cold oscillation of IV. Above this cold oscillation, III shows several small cold oscillations, with one stronger one between 579.5—608 cm. Below 799.5 cm. warm faunas prevail to the bottom sample where there is a decrease with a related increase in the cold fauna. The organic-rich layers described by Kullenberg (1952, p. 16) occur in both cold and warm periods. Only one sample, at 497.5 cm., contains too few planktonic specimens for analysis. *Globigerina eggeri* occurs at very high frequencies at 281.5 cm., 429.5 cm., 469.5 cm., and 527.5 cm., apparently more closely related to cooler periods although this is not true of the occurrence at 469.5 cm. *Globorotalia truncatulinoides* does not occur in the upper part of the core but shows right-coiling dominance in scattered samples from 209.5—419.5 cm. Below this point in IIc the occurrences are stronger and the coiling dominance fluctuates frequently to the bottom.

The benthonic population totals less than 50 specimens with the following exceptions: 169.5—90 cm., 429.5 cm., 449.5 cm., 532.5 cm., 629.5 cm., 699.5 cm., and 779.5—90 cm. The cold. fauna predominates in all the above sections At 699.5 cm., 1280 specimens of *Bulimina aculeata* occur; at 779.5 cm., 896 specimens. A single occurence of *Nonionella turgida* at

789.5 cm. is the only indication of displacement of shallow species into the core.

The following single-specimen occurrences have been omitted from Table 10: *Nonionella turgida* (86), *Patellina corrugata* (63), and *Uvigergina mediterranea* (45).

Core 190

Length sampled 930 cm.; depth 2900 m.; population counts given in Table 11.

The fauna at the top contains a high percentage of the cold fauna and appears to be below the top of IIa. IIa extends to 259.5 cm. with two cold maxima at 1—30 cm. and 39.5—70 cm., the lower one being of much lower frequency than the upper, as in all the cores. IIb extends from 259.5—379.5 cm. with two warm maxima at 259.5 cm. and 339.5—50 cm., the latter roughly corresponding to two maxima (319.5 cm., 350.5 cm.) in Core 189. IIc extends from 379.5—589.5 cm., showing several fluctuations but with three major cold ones at 379.5—400 cm., 418.5—29.5 cm., and 579.5 cm. III extends from 590 cm. to the bottom. There are two moderately large cold maxima at 749.5 cm. and 889.5 cm. but many minor oscillations may be resolved into four warm maxima at 589.5 cm., 659.5 cm., 779.5 cm., and 819.5 cm., the last two being closely linked. From 609—620 cm. a white streak was observed in the dark sediment of the core. The material of this white streak (Table 11, 65 B, 66 B) contains a warm fauna similar to that found in the section above from 560—600 cm. and probably derived from it. A crack in the sediment was probably filled by subsequent deposition. Only one sample, at 487 cm., contains too few Foraminifera for analysis. Very high frequencies of *Globigerina eggeri* occur at 469.5—83 cm., 609.5 cm., and 619.5 cm., all sections where the cold fauna predominates. *Globorotalia truncatulinoides* occurs from 210—60 cm. showing several fluctuations of right- and left-coiling dominance. From 439.5 cm. (in IIc) to 920 cm. (in III) the species is relatively abundant (except from 669—832 cm.) with two reversals in coiling direction in IIc and seven and a half reversals in III.

There are less than 50 benthonic specimens in all the samples analyzed with the following exceptions: 49.5 cm., 139.5 cm., 161.5—90 cm., 469.5 cm., 510.5 cm., 659.5 cm., and 869.5 cm. At all these levels, except 659.5 cm., the cold fauna is predominant. At 869.5 cm. the population is large, 768 specimens of *Bulimina aculeata* forming the major part. This occurrence may correlate with the lower abundant occurrence at 779.5 cm. in Core 189. There is very slight evidence of displacement from shallow water at 39.5 cm. and 109.5 cm. in single-specimen occurrences of *Nonionella turgida* and *Elphidium pulvereum* respectively.

The following single-specimen occurrences have been omitted from Table 11: *Astrononion stelligerum* (52), *Bolivina dilitata dilitatissima* (17), *B. pseudoplicata* (6), *Elphidium pulvereum* (13), *Gavelinopsis praegeri*, etc. (48, 55), *Globobulimina* ? sp. (40, 51), *Glomospira charoides* (6), *Neoconorbina williamsoni* (42, 68), *Nonionella turgida* (5), *Spirophthalmidium acutimargo* (18, 55), and *Virgulina mexicana* (70, 72).

Core 191

Length sampled 367.5 cm.; depth 3635 m.; population counts given in Table 12.

This core cannot be firmly correlated with adjacent ones (190, 192). The bottom profile given by Koczy (1956, profile 16) shows that this core was taken in a deep depression of the sea floor into which sediment may often be displaced by slumping. The presence of displaced species in various parts of the core shows that material has been carried here from relatively shallow depths. In Core 191 this material appears to have caused more disturbance of the normal sequence than usually happens, even when displaced Foraminifera are present. The sequence of warm and cold planktonic faunas does not follow the usual pattern observed in most of the other cores and for that reason no attempt has been made to interpret the geologic age of the cold and warm periods.

Both warm and cold faunas are present at the top of the core. The cold fauna increases rapidly with depth reaching a first maximum at 25.5 cm. and a somewhat higher one at 76.5—87 cm. Below this point the cold fauna declines rapidly and the warm fauna increases to a maximum at 139.5 cm. after which it, too, declines rapidly. The cold fauna then increases gradually to a maximum at 219.5—30 cm., decreasing gradually below. The warm fauna has a short period of predominance reaching a maximum at 350.5—53.5 cm. below which it declines and the cold fauna predominates increasingly to the bottom. Only one sample at 299.5 cm. contains too few planktonic specimens for analysis. *Globigerina eggeri* occurs at a very high frequency at 145.5 cm. *Globorotalia truncatulinoides* shows left-coiling dominance at the top, right-coiling dominance at 68.5 cm. (few specimens), and left coiling again at 96.5 cm. Several occurrences below show a gradual shift to maximum right-coiling dominance at 154.5 cm. Below this point the species occurs only once at 289.5 cm. with no definitive coiling direction.

No sample studied contains more than 62 benthonic specimens. Usually there are fewer. There is evidence of displacement of shallow species at 106.5 cm. and in most samples between 154.5—310 cm. based on various species of *Elphidium*, *Rosalina*, *Cibicides lobatulus*, etc.

The following single-specimen occurrences have been omitted from Table 12: *Bolivina albatrossi* (5, 14), *B. attica* (41), *Bulimina exilis* (10), *B. gibba* (40), *Cassidulina* cf. *C. sicula* (29), *Cassidulinoides tenuis* (10, 18), *Chilostomella mediterranensis* (3), *Cibicides lobatulus* (26, 32), *Eggerella bradyi* (11), *Elphidium advena* (34), *E. pulvereum* (19, 30), *Gyroidina* cf. *G. neosoldanii* (28, 33), *Hanzawaia rhodiensis* (14), *Neoconorbina terquemi* (26, 33), *Nonion* sp. A (33, 36), *Nonionella turgida* (33), *Patellina corrugata* (14, 34), *Planulina ariminensis* (2), *Pullenia quinqueloba* (34, 36), *Robulus* sp. (3), *Uvigerina auberiana* (14, 36), and *U. peregrina* (33).

Core 192

Length sampled 859 cm.; depth 2680 m.; population counts given in Table 13.

The fauna at the top is comparable to that of the present day. The cold fauna increases rapidly with depth to a maximum at 89.5 cm., the top of IIa. IIa extends to 458.5 cm., divided into two parts with maxima at 89.5 cm. and 379.5 cm. The former lessens gradually with minor fluctuations to 299.5 cm. and thus forms the major part of IIa. IIb extends from 458.5—620 cm. with warm maxima at 503 cm., 549.5—59.5 cm. and *ca.* 609.5 cm. IIc extends from 619.5—822 cm. with two cold maxima at 619.5—30 cm. and 779.5 cm., and a smaller cold oscillation at 719.5—30 cm. The top of III is placed tentatively at 822 cm. although the warm fauna below is not well-developed. This interpretation is based on comparison with adjacent cores (191, 193). No samples are barren of planktonic specimens. *Globigerina eggeri* does not occur at high frequencies. *Globorotalia truncatulinoides* shows right-coiling dominance at 14.5 cm., left coiling at 379.5 cm., right coiling at 397 cm., and left coiling at 488.5 cm. Below 759.5 cm. it occurs in several samples and shows several coiling-dominance fluctuations, mainly, however, left-coiling.

The benthonic population is usually less than 100 specimens with the following exceptions: 271.5 cm., 309.5—80 cm., 619.5 cm., 659.5—720 cm., 749.5 cm., 771—80 cm., and 801.5 cm. In all these samples the cold planktonic fauna predominates. There are 146 specimens of *Articulina tubulosa* and variants at 759.5 cm. There is evidence of displacement of benthonic specimens from shallow water throughout most of the core as shown by the presence of *Bolivina difformis*, *Cibicides lobatulus*, *Elphidium* spp., and *Rosalina* spp., etc. This displacement is easily explained by the proximity of the Island of Crete.

The following single-specimen occurrences have been omitted from Table 13: *Elphidium crispum* (38), *E. granosum* (77, 85), *P. verriculata* (76, 85), *Glomospira* cf. *G. gordialis* (1), *Lagenondosaria scalaris* (41, 79), *Planulina ariminensis* (41, 76), *Pullenia bulloides* (41, 85), *Rosalina suezensis* (26, 37), *Sphaeroidina bulloides* (41), *Streblus beccarii* var. (37), and *Textularia sagittula* (39, 69).

Core 193

Length sampled 622 cm.; depth 2130 m.; population counts given in Table 14.

In Figure 6 this core has not been correlated with adjacent ones nor has any age been assigned to the warm and cold periods reflected by the planktonic faunas. The character of these faunas and the presence of abundant occurrences of *Globorotalia truncatulinoides* in the upper two-thirds of the core point to the possibility that this section is comparable to the lower sections of some of the other cores, and that several meters may be missing from the top. If the top is correlated with the 350 cm. depth in Core 190 a reasonably good correlation can be made. Prof. Kullenberg (personal communication) says, however, that he is of the opinion that the loss from the top of the cores does not exceed one meter. According to the bottom profile given by Koczy (1956, profile 16) the core was taken on a topographic high and there is a possibility that material has slumped or been washed off by bottom currents leaving a lower section exposed.

The warm fauna is present to a greater or lesser extent almost throughout the core. The cold fauna predominates in the following sections: 9.5—190 cm., 229.5—92 cm., 309.5 cm., 329.5—60 cm., 389.5—409.5 cm., 429.5—90 cm., 519.5—60 cm., 579.5—600 cm., and in the bottom sample. The only indication of a major cold period, however, is from 9.5—200 cm. High frequencies of *Globigerina eggeri* occur at 339.5 cm. and 549.5 cm. *Globorotalia truncatulinoides* is present frequently to a depth of 410 cm., showing about nine shifts in coiling-direction dominance.

The benthonic populations are less than 100 specimens with the following exceptions: 79.5—120 cm., 149.5 cm., 229.5 cm., 309.5 cm., 339.5—50 cm., and 529.5—50 cm. In all the above sections the cold fauna is predominant. There are 278 specimens of *Bulimina aculeata* at 309.5 cm. This occurrence together with the high frequency occurrences of *Globigerina eggeri* are added evidence for the correlation of this core with the lower sections of adjacent ones. *Pyrgo serrata* is found in this core only, in four samples with an occurrence of 94 specimens at 339.5 cm. A few obviously displaced shallow specimens are scattered throughout but the displaced population is a minor constituent of the total benthonic population.

The following single-specimen occurrences have been omitted from Table 14: *Angulogerina angulosa* (11, 37), *Bolivina difformis* (57), *Cassidulina subglobosa* (8, 51), *Elphidium complanatum* (46), *E.* spp. (29, 57), *Globobulimina pseudospinescens* (51, 55), *Gyroidina altiformis* (2, 62), *Hanzawaia rhodiensis* (40), *Hyalinea balthica* (60), *Loxostomum alatum* (17), *Neoconorbina terquemi* (40, 41), *Nonion* sp. A (8, 64), *Patellina corrugata* (17, 36), *Planorbulina mediterranensis* (36), *Rosalina obtusa* (24, 26), *Siphotextularia concava* (17), *Uvigerina peregrina* (36, 45), and *Wiesnerella auriculata* (10).

Core 194

Length sampled 718.5 cm.; depth 3000 m.; population counts given in Table 15.

Both warm and cold faunas are present in the »top» sample at 2 cm. The warm fauna increases below to a maximum at 9.5 cm. This point is tentatively interpreted as representing the time of the »Climatic Optimum». The warm fauna decreases below and at 59.5 cm. the cold fauna appears at a high frequency. The top of Ia is at 69.5 cm. and extends to 389.5 cm., with two maxima at 149.5 cm. and 329.5 cm. IIb extends to 549.5 cm. and has two warm maxima at 389.5 cm. and 459.5 cm. with some additional minor fluctuations. IIc extends to the bottom but there are indications that the top of III is imminent. IIc has three cold maxima at 559.5—79.5 cm., 619.5 cm., and 679.5—83 cm. Most samples contain planktonic Foraminifera. *Globigerina eggeri* occurs at high frequencies at 424 cm. and 659.5 cm. Occurrences of *Globorotalia truncatulinoides* are rare, scattered throughout the core, and show mostly left-coiling dominance.

The benthonic population is less than 100 specimens with the following exceptions: 69.5 cm., 149.5—220 cm., 299.5—330 cm., 479.5—97.5 cm., 529.5 cm., 589.5—610.5 cm., 629.5—50 cm., and 692.7 cm. In all but the last section the cold fauna predominates. Displaced shallow specimens occur in most of the samples but are especially common from 69.5—330 cm. and 479.5—650 cm. Various species of *Elphidium* and *Rosalina* are common as well as many other shallow species. These comprise the major parts of the faunas in the cold periods IIa and IIc showing that not only are there more specimens of indigenous species in some parts of the cold-period sections but also more displaced specimens.

The following single-specimen occurrences have been omitted from Table 15: *Biloculinella labiata* (24), *Cibicides kullenbergi* (56, 74), *Elphidium complanatum* (33, 64), *E.* cf. *E. minimum* (25, 62), *Lenticulina peregrina* (31, 53), *Planulina ariminensis* (33), *Reussella spinosissima* (52, 56), *Rotamorphina? involuta* (66), *Siphonina reticulata* (56), *Siphotextularia concava* (31), *Spirillina wrightii* (56), *Textularia conica* (13), and *T. sagittula* (27).

Core 195

Length sampled 930 cm.; depth 3665 m.; population counts given in Table 16.

In the top sample the warm fauna is slightly predominant but neither cold nor warm fauna is well-developed. The cold fauna increases to a maximum at 9.5 cm., the top of IIa. Other cold maxima in IIa are at 109.5—20 cm., 229.5 cm., and 269.5 cm. These maxima resolve into two main divisions, the lower one, as in the other cores, being much smaller and shorter. IIb extends from 279.5—449.5 cm. with three warm maxima at 309.5—20 cm., 359.5 cm., and 379.5 cm. IIc extends from 450—759.5 cm. with several fluctuations, the chief maxima being at 449.5 cm., 539.5—50 cm., 659.5—70 cm., and 729.5 cm. III probably extends to the bottom although there is a fairly large cold fluctuation at the bottom of the core. III has two warm maxima at 759.5 cm. and 849.5—60.5 cm. Only four samples scattered throughout the core contain few or no planktonic specimens. *Globigerina eggeri* occurs at very high frequencies at 340.5 cm., 618.5—50 cm., and 779.5—800 cm. *Globorotalia truncatulinoides* occurs at the top with left-coiling dominance; at 299.5 cm. and 599.5 cm. right-coiling dominance is found. At 679.5 cm. and below the species is much more abundant than above, starting with left-coiling dominance and showing three coiling reverses below to 850 cm. Downward from this point it is absent.

The benthonic populations are less than 100 specimens except at the following depths: 129.5 cm., 259.5 cm., and 609.5 cm.; in all cases the cold fauna is predominant. At 259.5 cm. there are 106 specimens of *Articulina tubulosa* and variants; at 609.5 cm. there are 146 specimens. Displaced specimens occur throughout the core except at the following depths: 259.5 cm., 329.5—50 cm., 389.5—420 cm., 468.5 cm., 649.5 cm., 689.5 cm., 719.5 cm., 739.5—50 cm., 769.5 cm., 849.5—60.5 cm., and 889.5 cm. The displaced shallow specimens, however, form a relatively small part of the benthonic population. They belong to such species as *Cibicides lobatulus* ,*Elphidium pulvereum*, *Rosalina* spp., etc.

The following single-specimen occurrences have been omitted from Table 16: *Biloculinella labiata* (14), *Bolivina catanensis* (71), *Bulimina costata* (24), *Elphidium advena* (53), *P. verriculata* (44, 69), *Hanzawaia rhodiensis* (83), *Rosalina obtusa* (61, 74), and *Spirophthalmidium acutimargo* (9, 92).

Core 196

Length sampled 650 cm.; depth 4270 m.; population counts given in Table 17.

According to the bottom profile given by Koczy (1956, profile 16), this core was taken in a deep depression of the ocean floor. It correlates well, however, with the adjacent Core 195. At the top there is a trace of the warm fauna present but the cold fauna increases rapidly with depth to a maximum at 29.5 cm., the top of IIa. IIa extends to 349.5 cm. showing several fluctuations, the strongest of which are at 29.5—149.5 cm., and 209.5—40 cm., the lower one being much smaller and shorter. IIb extends from 350—569.5 cm. with four warm maxima at 349.5—70 cm., 419.5 cm., 459.5 cm., and 539.5 cm. IIc extends from 569.5 cm. to the bottom. In addition to isolated samples, planktonic specimens are few or absent from 259.5—90 cm., and in several samples from 438—561 cm. *Globigerina eggeri* occurs at very high frequencies at 379.5—91 cm., and 501.5 cm. *Globorotalia truncatulinoides* is found in only five samples: at 9.5 cm. with 55 % left-coiling dominance, at 249.5 cm. with 77 % right-coiling, and with fluctuating coiling dominance below in occurrences with are too small to give statistically valid results.

The benthonic populations are less than 100 specimens except at the following depths: 29.5 cm., 499 cm., and 579.5 cm. All these occurrences are in sections where the cold planktonic fauna predominates. The smallest benthonic populations occur from 329.5—460 cm. and 501.5—40 cm., sections where the warm planktonic fauna predominates. Rare specimens displaced from shallow water are found scattered throughout most of the core, but are expecially abundant at 579.5 cm.

The following single-specimen occurrences have been omitted from Table 17: *Bolivina albatrossi* (60), *Eggerella bradyi* (60), *Elphidium complanatum* (60), *E. pulvereum* (49, 64), *Epistominella rugosa convexa* (44), *Gyroidina delicata* (7, 60), *G.* cf. *G. neosoldanii* (60), *G. umbonata* (51), *Karreriella bradyi* (34), *Nonion barleeanum* (48), *Nonionella turgida* (60), *Rosalina globulosa bradyi* (8), *Sigmoilina tenuis* (22), *Spirophthalmidium acutimargo* (49), and *Streblus beccarii* var. (7, 22).

Core 197

Length sampled 730 cm.; depth 2940 m.; population counts given in Table 18.

This core differs from the adjacent ones (196, 198) in the greater prevalence of the warm fauna which is present apparently even in most of what appears to be the IIc cold period. On Figure 6 tentative correlations have been made but they are not as clearly defined as usual. The cold fauna is found at the top increasing to a maximum at 9.5 cm., the top of IIa. IIa extends to 259.5 cm. showing two maxima at 9.5—60 cm. and 149.5 cm. IIb extends from 259.5—539.5 cm. In IIb the warm fauna shows many oscillations which may be resolved into five warm maxima at 259.5 cm., 310 cm., 409.5 cm., 451 cm., and 530 cm. The top of IIc is placed tentatively at 539.5 cm. although the warm fauna continues below. It is overshadowed, however, by the cold fauna all the way to the bottom of the core except in the section from 649.5—679 cm. The cold fauna shows four maxima at 539.5 cm., 569.5—90 cm., 639.5 cm., and 689.5 cm. Only a few isolated samples have few or no planktonic specimens. *Globigerina eggeri* occurs at very high frequencies at 141.5 cm., 310 cm., and 419.5 cm. *Globorotalia truncatulinoides* is found frequently to a depth of 230 cm., being absent below this point. At 1 cm. it shows right-coiling dominance, below the dominance is left coiling to varying degrees. The only occurrence in the eastern Mediterranean material of *Globorotalia punctulata* is in this core at 609.5 cm.

The benthonic population is below 50 specimens in all the samples studied except the one at 99.5 cm. (98 specimens). Possibly displaced specimens occur at 559.5 cm. and 799.5 cm.

The following single-specimen occurrences have been omitted from Table 18: *Bolivina dilitata dilitatissima* (16), *B. pseudoplicata*(1), *Bulimina exilis* (15), *Cassidulina* cf. *C. oblonga* (2), *C. subglobosa* (34), *Elphidium* sp. (60), *Neoconorbina terquemi* (74), *Pyrgoella sphaera* (11), *Robulus* sp. (73), *Spiroloculina canaliculata* (27, 49), and *Wiesnerella auriculata* (1).

Core 198

Length sampled 1149 cm.; depth 3555 m.; population counts given in Table 19.

According to the depth profile given by Koczy (1955, profile 16) this core was taken in a depressed area. The sequence of the warm and cold periods, however, appears to be normal. The warm fauna predominates at the top but decreases rapidly with depth with the exception of one minor warm oscillation at 29.5 cm. The cold fauna reaches a maximum at 49.5 cm., the top of IIa. IIa extends to 508.5 cm. with several cold maxima, the chief ones at 49.5 cm., 97.5 cm., 269.5 cm.; the lesser ones at 319.5 cm., and 419.5 cm. IIb extends from 509—719.5 cm. with three warm maxima at 509 cm., 570.5—80.5 cm., and 669.5—90 cm. IIc extends from 719.5—1009.5 cm. with four cold maxima at 719.5—40 cm., 819.5—30 cm., 879.5 cm., and 929.5 cm. III extends from 969.5 cm. to the bottom. There is a cold period from 1069.5 cm. to the bottom but this is believed to correlate with the short cold oscillation found in the upper part of III in several cores. In Core 198 it has a somewhat longer extent as do all the thermal sections of the core. There are no planktonic Foraminifera in the sections at 60—97.5 cm., 120—69.5 cm., 450—508.5 cm., nor in several isolated samples. *Globigerina eggeri* occurs at very high frequencies at 879.5—90 cm. and 1009.5 cm. *Globorotalia truncatulinoides* shifts from left-coiling dominance at 19.5 cm. to right-coiling dominance at 29.5 cm. This is maintained in isolated samples to 570.5 cm. Below this point the species is absent to 949.5 cm. where left coiling is dominant. There are three further coiling-direction oscillations to 1061 cm., below which the species is absent.

The benthonic population is less than 50 specimens in all samples studied except at 879.5 cm. Benthonic specimens are absent from 570.5—670 cm. and 978.5—1020 cm., both sections being where the warm planktonic fauna is predominant. Single specimens of *Elphidium* sp., *E. crispum* and *E. pulvereum* at 1 cm., 97.5 cm., and 899.5 cm. respectively, and a single specimen of *Nonion* sp. A at 899.5 cm. are the only evidences of the presence of displaced shallow forms.

The following single-specimen occurrences have been omitted from Table 19: *Bolivina albatrossi* (11), *Bulimina costata* (11), *B. marginata* (93), *Cassidulina carinata* (93), *Elphidium crispum* (11), *E. pulvereum* (93), *E.* sp. (1), *Loxostomum alatum* (93), *Nonion* sp. A (93), *Pseudoeponides umbonatus* var. (93), *Pullenia quinqueloba* (11), *P.* cf. *P. riveroi* (110, 111), *Robulus* sp. (28), and *Sigmoilina tenuis* (93).

Core 199

Length sampled 847 cm.; depth 2370 m.; population counts given in Table 20.

The warm fauna is predominant at the top but disappears immediately below with a corresponding increase in the cold fauna. IIa extends from 9.5—442.5 cm. with several fluctuations. Cold maxima occur at 9.5 cm., 92.5 cm., 123.5—40 cm., 255.5—67 cm., and 317.5—56 cm. Many of these are probably not indicative of true maximal conditions but merely reflect minor faunal fluctuations. IIb extends from 443—599.5 cm. with three small warm maxima at 442.5 cm., 473.5—84 cm., and 529.5—40 cm. IIc extends from 599.5 cm. to the bottom, although there is a possibility that III starts near the bottom of the core. IIc has cold maxima at 599.5 cm., 723.5 cm., and 767.5 cm. with minor fluctuations in addition. Several isolated samples contain few or no Foraminifera. There are no very high frequency occurrences of *Globigerina eggeri*, the highest (34—5 %) being from 492.5—500 cm. *Globorotalia truncatulinoides* shows left-coiling dominance at the top and is absent below for about five meters. At 492.5 cm. it shows right-coiling dominance. Below 713.5 cm. there are numerous occurrences all with left-coiling dominance.

The benthonic populations are always less than 65 specimens. As in the other cores the larger populations usually occur when the cold fauna is predominant. Displaced specimens from shallow water occur at the top, 169.5—256 cm., 310.5 cm., 362.5 cm. (?), 442.5 cm., 473.5 cm., and 549.5 cm. Such species as *Elphidium crispum*, *E. pulvereum*, *Rosalina* aff. *R. columbiensis*, etc., occur in these sections.

The following single-specimen occurrences have been omitted from Table 20: *Angulogerina angulosa* (1), *Bulimina marginata* (54, 80), *Cassidulina* cf. *C. oblonga* (1, 67), *Cibicides lobatulus* (1, 54), *C. wuellerstorfi* (14), *Elphidium advena* (19, 62), *E. granosum* (35, 50), *Epistominella rugosa convexa* (54), *Glomospira charoides* (1), *Hanzawaia rhodiensis* (54, 62), *Loxostomum alatum*, (1, 62), *Neoconorbina terquemi* (56), *Nonion* sp. B (19), *Planulina ariminensis* (54), *Pyrgo lucernula* (50, 77), *Rosalina obtusa* (1), *Sigmoilina tenuis* (10, 23), *Spirophthalmidium acutimargo* (23), *Streblus beccarii* var. (1), *Valvulineria complanata* (28, 69), and *Virgulina mexicana* (19).

Core 200

Length sampled 80 cm.; depth 2050 m.

The length of this core when collected was 498 cm. (Kullenberg, 1955), but the greater part of the core was semi-liquid so that no suitable samples could be taken for study. The section sampled contains a large quantity of sand. A few planktonic and a larger number of benthonic specimens occur. Many of the benthonic species suggest that much of the material was displaced from shallow water. Sedimentation appears to have been very rapid since planktonic specimens are usually scarce. No interpretation of climatic conditions based on them has been attempted.

Some of the most common benthonic species found are: *Bolivina catanensis*, *Bulimina marginata*, *B. costata*, *Cassidulina carinata*, *C.* cf. *C. oblonga*, *Elphidium advena*, *E. pulvereum*, *Gyroidina* cf. *G. neosoldanii*, *Nonion barleeanum*, etc. (usually *N. formosum*), *Valvulineria complanata*, and *Virgulina mexicana*.

Appendix B: Systematic Descriptions

This section includes discussions of 18 planktonic and 110 benthonic species and subspecies, of which 1 planktonic and 4 benthonic forms are new. The benthonic species described make up most of the benthonic population of the surface sediments and cores with the possible exception of those of the littoral and sublittoral zones. Many shallow-water species have been grouped together as *Elphidium* spp., Miliolidae, Peneroplidae, and *Rosalina* spp., since the individual species are represented in the samples by relatively few specimens. Taken together, however, these groups form an important part of some populations. The species of *Robulus* are grouped under *Robulus* spp. for the same reason. Additional species of which there are a considerable number are included in Tables 6—20 as »miscellaneous species».

Many of the benthonic species are widespread in the North Atlantic or occur along the coasts of Africa, Europe, and the British Isles. About 25 % appear to be indigenous to the Mediterranean. Of the planktonic species only *Globigerinoides tenella* n. sp. has not been reported elsewhere, and may have been overlooked previously because of its small size.

Distributions in the surface sediment samples and cores are given for each benthonic species, with the depth distribution in the North Atlantic for comparison, when available. Most species are figured with the exception of a few, very well known, distinctive forms. The figured specimens have been deposited in the U. S. National Museum, Washington, D. C.

Benthonic Species

Family TOLYPAMMINIDAE

Glomospira charoides (Jones and Parker)

Trochammina squamata Jones and Parker var. *charoides* Jones and Parker, 1860, Quart. Journ. Geol. Soc., vol. 16, p. 304.

Trochammina charoides Jones and Parker. Carpenter, Jones and Parker, 1862, Introd. Foram., p. 141, pl. 11, fig. 3.

This species is reported deeper than 200 m. in the North Atlantic. It is found at thirty-two stations from 115—3499 m. (up to 100 %) with highest frequencies deeper than 731 m., at four stations showing displacement, and in scattered samples in Cores 184, 186, 187, 189, 190, 192, 197, and 199.

Glomospira cf. **G. gordialis** (Jones and Parker)

The specimens are similar to those referred by Phleger *et al.* (1953, p. 26, pl. 5, fig. 2) to Jones and Parker's (1860, p. 304, *Trochammina squamata* var. *gordialis*) species. It is found at fourteen stations from 567—3241 m. (up to 10 %) and at three stations showing displacement, but was not observed in the cores.

Involutina cf. **I. planorbis** (Höglund)
(Plate 1, figures 1, 2)

Mediterranean specimens are larger than Höglund's (1947, p. 125, pl. 8, figs. 4, 9; pl. 28, figs. 13, 14; text figs. 91, 105, 109— *Ammodiscus*) which have a maximum diameter of 0.70 mm. and a proloculus size for megalospheric forms of 29 (21—40) μ. However, he also questionably refers to his species specimens from off Portugal which have a maximum diameter of 1.40 mm. and a proloculus size for megalospheric forms of 75 (69—82) μ. The Mediterranean specimens have a maximum diameter of 0.90 mm. and a proloculus size of 60 (40—81) μ. It is possible that these measured specimens include some microspheric forms since the maximum proloculus size is almost the same as that of the Portugal specimens but the minimum is considerably less. As Höglund points out it is sometimes difficult to be sure whether specimens are megalospheric or microspheric.

This species is found at twenty stations from 143—2442 m. (up to 8 %) with the highest frequencies deeper than 665 m., at two stations showing displacement, and in two samples of Core 184.

Family TEXTULARIIDAE

Bigenerina nodosaria d'Orbigny

Bigenerina nodosaria d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 261, no. 1, pl. 11, figs. 9—12; Modèles, no. 57.

This species has been reported from various shallow localities in the Mediterranean. Many reported occurrences outside of this area may be erroneous. It is found at twenty-one stations from 71—799 m. (up to 5 %) and at one station showing displacement, but was not observed in the cores.

Siphotextularia concava (Karrer)

Plecanium concava Karrer, 1868, Sitz. k. Akad. Wiss. Wien, vol. 58, Abth. 1, p. 129, pl. 1, fig. 3.

This species is found at fifteen stations from 51—631 m. (up to 2 %), at three stations showing displacement, and in a few samples in Cores 192—194 associated with displaced faunas

Textularia calva Lalicker

(Plate 1, figures 3, 4)

Textularia calva Lalicker, 1935, Smithsonian Misc. Coll., vol. 91, no. 22, p. 1, pl. 1, figs. 1, 2.

Mediterranean specimens are very similar to this species. Specimens (in the U. S. National Museum) from the coast of the Island of Delos have been so identified by Lalicker. The sutures are less depressed and more obscure than those of *T. agglutinans* d'Orbigny, and the wall is more coarsely arenaceous. The chambers increase in size less rapidly as added than in *T. candeiana* d'Orbigny. *T. calva* is found at twenty-one stations from bay-567 m. (up to 5 %) and occurs rarely in Core 200.

Textularia conica d'Orbigny

(Plate 1, figures 5, 6)

Textularia conica d'Orbigny, 1839, *in* de la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foraminifères», p. 143, pl. 1, figs. 19, 20.

This species is reported from the West Indies from 16—400 m. It is found at eighteen stations from 51—631 m. (up to 3 %), at one station showing displacement, and in one sample of Core 194 associated with a displaced fauna.

Textularia sagittula Defrance

Textularia sagittula Defrance, 1824, Dict. Sci. Nat., vol. 32, p. 177; Atlas Conch., pl. 13, fig. 5.

This species is sometimes referred by writers on the Mediterranean Foraminifera to »*Spiroplectammina wrightii*» (Silvestri). Lacroix (1929) has demonstrated clearly that the two species are synonymous. *T. sagittula* is found at eighteen stations from 51—366 m. and at 731 m. (up to 9 %) with the highest frequencies shoaler than 201 m., at two stations showing displacement, and in Cores 192 (twice) and 194 (once) associated with displaced faunas.

Family VERNEUILINIDAE

Pseudoclavulina crustata Cushman

(Plate 1, figure 7)

Pseudoclavulina crustata Cushman, 1936, Cushman Lab. Foram. Res., Spec. Publ. 6, p. 19, pl. 3, figs. 12 a, b.

Mediterranean specimens are identical to Cushman types from off Greece. They are found at eighteen stations from 107—731 m. (up to 5 %) but do not occur in the cores.

Family VALVULINIDAE

Eggerella bradyi (Cushman)

(Plate 1, figure 8)

Verneuilina pygmaea Brady, 1884 (not *Bulimina pygmaea* Egger, 1857), Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 385, pl. 47, figs. 4—7.

Verneuilina bradyi Cushman, 1911, U. S. Nat. Mus., Bull. 71, pt. 2, p. 54, text figs. 87 a, b.

A discussion of this species is given by Phleger *et al.* (1953, p. 27). Included in the population counts are occasional specimens of adult *Karreriella bradyi* (Cushman) (pl. 1, fig. 9). Both species have been reported from the North Atlantic: *E. bradyi* deeper than *ca.* 600 m., *K. bradyi* deeper than 155 m. *E. bradyi* is found at one station showing displacement and in all the cores, except Cores 195, 198, and 200, in varying abundance.

Family MILIOLIDAE

The more common species have been identified and discussed separately. There remains, however, a large number of species (rarely represented) grouped together as »Miliolidae» in the population counts. »Miliolidae» occur at almost all stations to a depth of 1378 m. and at a few deeper ones. The highest frequencies (up to 40 %) are found shallower than 180 m.; deeper than this they do not exceed 6 % except at two deep stations where there are very few benthonic specimens. »Miliolidae» are found in all the cores.

Articulina tubulosa (Seguenza) and vars.
(Plate 1, figures 12, 13, 18, 19)

Quinqueloculina tubulosa Seguenza, 1862, Atti Accad. Gioenia Sci. Nat., ser. 2, vol. 18, p. 35, pl. 2, fig. 8.

This species appears to be a true *Articulina* although the prolongation of the uniserial chambers is unique for the genus. The species is very variable in several respects. The length of the initial quinqueloculine portion varies from *ca.* 0.07—0.43 mm. In some specimens it has a sharply angled periphery, in others a narrowly rounded one. Specimens are observed in all stages of development from those with only the quinqueloculine portion to those having three uniserial chambers. The former are more abundant but whether these are normal specimens or specimens from which the long fragile uniserial portion has been broken cannot be stated. This species occurs at five stations deeper than 684 m. (up to 20 %) and at two stations showing displacement. The highest frequencies occur deeper than 3000 m. This is one of the most abundant species in the cores and appears to be a true deep-sea form.

Biloculinella labiata (Schlumberger)
(Plate 1, figures 10, 11)

Biloculina labiata Schlumberger, 1891, Mém. Soc. Géol. France, vol. 4, p. 556, text figs. 13, 14; pl. 9, figs. 60—62.

The ratio of thickness to width of Schlumberger's figured specimens varies from 1:1.05 to 1:1.96. The specimens found in this study are more compressed, having ratios of thickness to width varying from 1:1.2 to 1:2.3. In other respects they are typical. Schlumberger reports the species from a depth of 555 m. in the Mediterranean. It occurs at twenty-one stations from 106—1378 m. (up to 5 %) mostly deeper than 287 m., at four stations showing displacement, and is associated with displaced faunas in Cores 188, 192, 194, and 195.

Miliolinella circularis (Bornemann)
(Plate 1, figures 16, 17)

Triloculina circularis Bornemann, 1855, Zeitschr. deutsch. Geol. Ges., vol. 7, p. 349, pl. 19, fig. 4.

Mediterranean specimens (max. length 0.58 mm.) are very like Bornemann's (length 0.42 mm.) except for their larger size. This is a much less compressed species than *M. dilitata* (d'Orbigny). It is found at thirty-three stations from bay-3309 m. (up to 5 %), at seven stations showing displacement, and is one of the most common species in the cores.

Pyrgo anomala (Schlumberger)
(Plate 1, figures 22, 23)

Biloculina anomala Schlumberger, 1891, Mém. Soc .Zool. France, vol. 4, p. 182, pl. 11, figs. 84—86; pl. 12, fig. 101; text figs. 32—34.

Schlumberger gives a maximum length for this species of 0.8 mm. The specimens included here have a maximum length of 0.97 mm. but in other respects appear identical. There is considerable variation in the relative width of the tooth. The species is found at sixteen stations from 75—684 but mostly deeper than 115 m. (up to 3 %), at two stations showing displacement, and in Cores 184, 186, 187, 189—194, 199, and 200.

Pyrgo lucernula (Schwager)

(Plate 1, figure 15)

Biloculina lucernula Schwager, 1866, Novara Exped., Geol. Theil., vol. 2, p. 202, pl. 4, figs. 14, 17.

This species is not found in the surface sediments but occurs in varying abundance in Cores 184, 186—190, 192, 193, 197, 199 and 200.

Pyrgo murrhina (Schwager)

Biloculina murrhina Schwager, 1866, Novara Exped., Geol. Theil., vol. 2, p. 203, pl. 4, figs. 15 a—c.

Mediterranean specimens vary in the same way as those reported by Phleger *et al.* (1953, p. 28, pl. 5, figs. 22—24). The species is found at one station at 3309 m. (5 %), and occurs in varying abundance in all cores except Cores 196 and 200.

Pyrgo serrata (Bailey)

Biloculina serrata Bailey, 1861, Boston Journ. Nat. Hist., vol. 7 (1859—1863), no. 3, p. 350, pl. 8, fig. E.

This species is found only in Core 193 (4 samples) in relatively large numbers (up to 94 specimens). For this reason it is included when other such rare species are omitted.

Pyrgoella sphaera (d'Orbigny)

(Plate 1, figure 14)

Biloculina sphaera d'Orbigny, 1839, Voy. Amér. Mérid., vol. 5, »Foraminifères», p. 66, pl. 8, figs. 13—16.

This species is found at one station at 82 m. (less than 1 %), at three stations showing displacement, and in Cores 184, 186, 188—190, 192—195, 197, and 198.

Quinqueloculina aff. Q. lamarckiana d' Orbigny

(Plate 1, figures 20, 21)

Mediterranean specimens have a less sharply angled periphery than d'Orbigny's (1839, p. 189, pl. 11, figs. 14, 15) species. In addition the Mediterranean form has a much deeper depth range than that given for *Q. lamarckiana* in other areas (usually shoaler than 300 m.). It is very probable that this form is not related to *Q. lamarckiana* but the writer is reluctant to add to the list of new miliolid species in the Mediterranean in view of the great number that have already been described in that area. It is very possible that this form, which is common, should be referred to one of these described species but available types must be viewed before this can be done since it apparently does not resemble any of the species as figured. It is found at nineteen stations from 75—1016 m. but mostly shallower than 680 m. (up to 2 %), at three stations showing displacement, and in varying abundance in all cores except Cores 191, 196, and 200.

Sigmoilina distorta Phleger and Parker

(Plate 1, figure 25)

Sigmoilina distorta Phleger and Parker, 1951, Geol. Soc. America, Mem. 46, pt. 2, p. 8, pl. 4, figs. 3—5.

Many specimens are typical but same are less sigmoid and compressed. The species is found at twenty-three stations from 51—731 m. (up to 2 %), at 3309 m. (45 %), at two stations showing displacement, and in Cores 192 and 200 associated with displaced faunas.

Sigmoilina schlumbergeri Silvestri

Planispirina celata Costa, sp. Schlumberger, 1887, Bull. Soc. Zool. France, vol. 12, p. 111 (481), text figs. 6, 7; pl. 7, figs. 12—14 (*Sigmoilina* (*Planispirina*) *celata* in expl. of pl.).

Sigmoilina schlumbergeri Silvestri, 1904, Mem. Pont. Accad. Nuovi Lincei, vol. 22, p. 267.

This species is reported from the North Atlantic deeper than 80 m. It is found at eighteen stations from 179—1016 m. (up to

4 %), at two stations showing displacement, in three samples of Core 193, and one sample of Core 196 associated with displaced faunas.

Sigmoilina tenuis (Czjzek)

(Plate 1, figure 24)

Quinqueloculina tenuis Czjzek, 1848, Haidinger's Nat. Abhandl., vol. 2, p. 149, pl. 13, figs. 31—34.

This species is reported in the Bay of Naples deeper than 200 m. It is found at ten stations from 205—1016 m. (up to 1 %), at five stations showing displacement, and in Cores 184, 186, 188, 192—194, 196, 198, and 199.

Spiroloculina angulosa Terquem

(Plate 1, figures 29, 30)

Spiroloculina angulosa d'Orbigny [nomen nudum], 1826, Ann. Sci. Nat., vol. 7, p. 298, no. 9; Terquem, 1878, Mém. Soc. Géol. France, ser. 3, vol. 1, p. 53, pl. 5 (10), fig. 7.

Rare specimens of *S. depressa* d'Orbigny may be included in the population counts but in most cases typical *S. angulosa* occurs. It is found at eleven stations from 71—541 m. and at 1016 m. (up to 1 %), at three stations showing displacement, and in a few samples in Cores 188 and 192 associated with displaced faunas.

Spiroloculina canaliculata d'Orbigny

(Plate 1, figures 26, 27, 28)

Spiroloculina canaliculata d'Orbigny, 1846, Foram. Foss. Bass. Tert. Vienne, p. 269, pl. 16, figs. 10—12.

Mediterranean specimens are larger and thicker than those of the Vienna Basin Miocene with a maximum length of slightly more than 1.0 mm. and a maximum thickness of 0.25 mm. Some of the specimens have a very wrinkled periphery (*vide* pl. 1, fig. 27). This species is found at nineteen stations from 21—1016 m. (up to 1 %), at three stations showing displacement, and in Cores 184, 186—189, 192—194, 197, and 199 but rarely except in Cores 192 and 193.

Spiroloculina grata Terquem

(Plate 1, figure 31)

Spiroloculina grata Terquem, 1878, Mém. Soc. Géol. France, ser. 3, vol. 1, p. 55, pl. 5 (10), figs. 14 a—15 b.

This species is found at fifteen stations from bay—859 m. but mostly shallower than 287 m. (up to 2 %), at six stations showing displacement, and in Cores 188, 192, and 194—196, associated with displaced faunas.

Family OPHTHALMIDIIDAE

Spirophthalmidium acutimargo (Brady)

Spiroloculina acutimargo Brady (part), 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 154, pl. 10, fig. 13 (*not* figs. 12, 14, 15).

Included in the populations counts are a few specimens of the concavo-convex form referred by Heron-Allen and Earland (1916, p. 208, pl. 39, figs. 1—3) to »*Spiroloculina acutimargo* var. *concava*». It is probable that these are merely variant forms of *S. acutimargo*. This species is found at sixteen stations from 205—1378 m. (up to 14 %), at five stations showing displacement, and in scattered samples in all the cores except Cores 191, 197, 198, and 200.

Wiesnerella auriculata (Egger)

Planispirina auriculata Egger, 1893, Abhandl. k. bay Akad. Wiss. München, Cl. II, vol. 18, p. 245, pl. 3, figs. 13—15.

This species is not found in the surface sediments but occurs in Cores 192—197.

Family PENEROPLIDAE

Representatives of this family are found only at Sta. B. S. 32 in Piraeus Harbor (6 %).

Family LAGENIDAE

Lagenonodosaria scalaris (Batsch)

(Plate 1, figures 32, 33)

Nautilus (*Orthoceras*) *scalaris* Batsch, 1791, Conch. des Seesandes, no. 4, pl. 2, figs. 4 a, b.

This species is assigned by some authors to the genus *Amphicoryna* Schlumberger but the writer is not sure that the rare specimens having a coiled initial portion are referrable to Batsch's species and it is, therefore, referred here to *Lagenonodosaria*. It is found at twenty-four stations from 82—996 m. (up to 5 %), at five stations showing displacement, and rarely in Cores 188, 192, 194, and 200, associated with displaced faunas.

Lenticulina peregrina (Schwager)

Cristellaria peregrina Schwager, 1866, Novara Exped., Geol. Theil., vol. 2, p. 245, pl. 7, fig. 89.

This species is reported in the North Atlantic deeper than 90 m. It is found at eight stations from 567—1016 m. (up to 2 %), at three stations showing displacement and in Cores 192 and 200 associated with displaced faunas.

Robulus spp.

Specimens of this genus are found at twenty-eight stations from 51—1016 m. (up to 4 %), at five stations showing displacement, and in scattered samples in all the cores except Cores 195 and 196.

Family NONIONIDAE

Astrononion stelligerum (d'Orbigny)

(Plate 1, figures 34, 35)

Nonionina stelligera d'Orbigny, 1839, *in* Barker-Webb and Berthelot, Hist. Nat. Iles Canaries, vol. 2, pt. 2, »Foraminifères», p. 128, pl. 3, figs. 1,2.

As pointed out previously (Parker, 1952, p. 410, »*Astrononion stellatum* Cushman and Edwards») this species is similar to *A. gallowayi* Loeblich and Tappan but differs in having 8—10 (usually 9—10) chambers in the final whorl and more inflated chambers. It is found at ten stations from 51—1016 m. (up to 2 %) with only two occurrences deeper than 179 m. (0.3 %), at one station where there are many displaced specimens, and associated with displaced faunas in Cores 192, 194, and 195.

Nonion barleeanum (Williamson), etc.

(Plate 1, figures 36, 37)

Nonionina barleeana Williamson, 1858, Rec. Foram. Great Britain, p. 32, pl. 3, figs. 68, 69.

This species has been combined with *N. formosum* (Seguenza) (pl. 1, figs. 38, 39) in the population counts since the two species usually occur together and are difficult to differentiate when counting. Both species have test walls showing a granular structure (Bramlette, personal communication). The related species, *N. pompilioides* (Fichtel and Moll), does not occur. The species are found (one or both) at thirty-seven stations from 51—3974 m. (up to 42 %) and in Cores 184, 186, 188, 191—194, 199, and 200, usually associated with displaced faunas. The reason for this association with displaced species is unknown since both have a deep range. It has been noted previously that there is frequently an increase in the number of deep ranging species present in samples which contain presumably displaced shallow species.

Nonion sp. A

(Plate 1, figures 42, 43)

This is a small (max. diam. 0.34 mm.), thin-walled species, compressed, with 9—10 chambers in the final whorl. The umbilical area and inner parts of the sutures are usually filled with fine papillae. The wall has a granular structure and the perforations, if present, are smaller than 2—3 μ (Bramlette, personal communication). The species is apparently new but insufficiently common to describe as such. It is not found in the surface sediments but occurs

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in Cores 191—196, and 198 associated with displaced faunas. The uppermost occurrence in the samples studied is at 9.5 cm. in Core 195, but usually it appears much lower in the section.

Nonion sp. B

(Plate 1, figures 40, 41)

This is a small (max. diam. *ca.* 0.37 mm.), rather compressed species with a thickened keel, incised sutures, an umbilical plug, and 9—12 chambers in the final whorl. The sutures appear to have small retral processes, although they are difficult to detect. The wall is granular and so finely perforate that the pores are not visible when viewed with a magnification of 250 X (Bramlette, personal communication). This species, like the previous one, is probably new but is insufficiently common to describe as such. It is found at five stations from 51—567 m. (up to 1 %), at three stations showing displacement, and in Cores 188, 191, 192, 194—196, and 199, associated with displaced faunas.

Nonionella turgida (Williamson)

Rotalina turgida Williamson, 1858, Rec. Foram. Great Britain, p. 50, pl. 4, figs. 95—97.

It is possible that occasional specimens referrable to *N. opima* Cushman are included in the population counts. *N. turgida* is found at three stations from 86—567 m. (less than 1 %), at one station showing displacement, and in scattered samples in Cores 187—194, 196, and 200, associated with displaced faunas.

Family BULIMINIDAE

Angulogerina angulosa (Williamson)

(Plate 2, figures 1, 2)

Uvigerina angulosa Williamson, 1858, Rec. Foram. Great Britain, p. 67, pl. 5, fig. 140.

Specimens are usually somewhat broader relative to length than most of those from the British Isles, but identical ones have been observed in material from the vicinity of Ireland. The species is reported from shallow stations in the British Isles. Parker (1948) reports it from the continental shelf of the eastern United States deeper than 63 m. It is found at seven stations from 179—731 m. (up to 4 %), at three stations showing displacement, and associated with displaced faunas in Cores 188, 191—195, and 199.

Bolivina albatrossi Cushman

(Plate 2, figures 3, 4)

Bolivina albatrossi Cushman, 1922, U. S. Nat. Mus., Bull. 104, pt. 3, p. 31, pl. 6, fig. 4.

This species is reported in the North Atlantic and the Gulf of Mexico deeper than *ca.* 200 m. but is confined to deeper water sediments in the eastern Mediterranean. It is found at five stations from 567—1378 m. (up to 4 %), at four stations showing displacement, and in varying abundance in eleven cores, most commonly in Cores 184 and 186. That the depth range may be deeper than that shown by the distribution in surface sediment samples is suggested by the absence of displaced shallow specimens in the core samples in which the species is found.

Bolivina attica Parker, n. sp.

(Plate 2, figures 12, 13, 14)

Test medium in size, very slightly tapering, ratio of length to width *ca.* 1: 3, often terminated by a short, stubby spine; periphery sharply angled to slightly rounded, often with a narrow keel; chambers narrow, up to 23 in number; sutures flush with the surface, slightly limbate, especially in the upper part of the chamber, slightly curved, slanting at an angle of about 45° except near the outer part of the test where the downward slope is steeper; wall with medium-sized perforations, ornamented on the lower half of the test with 10—12 low costae. Maximum length 0.65 mm., width 0.2 mm., thickness 0.1 mm.

The holotype (U. S. N. M. P6123) and figured paratypes (U. S. N. M. P6124 a, b) are from the

Aegean Sea, Atlantis Sta. B. S. 20 (Cruise 151), Lat. 39° 19′ N., Long. 26° 00′ E., at a depth of 210 m.

This species is not variable except in the character of the periphery which is usually keeled but sometimes slightly rounded, especially in the initial portion. As is usual in this genus, the microspheric form, being more pointed at the initial end, is more tapered. *B. attica* differs from *B. acutula* Bandy (originally *B. advena* Cushman var. *acutula* Bandy) in its greater length and compression, coarser perforations, basal spine, more numerous chambers, and straighter sutures and from *B. striatula* Cushman in its greater length and compression, undepressed sutures, and small terminal spine.

This species is found at eight stations from 82—338 m. (up to 2 %), at one deep station containing displaced specimens, and rarely in Cores 188, 191, 192, and 194, associated with displaced faunas.

Bolivina catanensis Seguenza

(Plate 2, figures 10, 11)

Bolivina catanensis Seguenza, 1862, Atti Accad. Gioenia Sci. Nat., ser. 2, vol. 18, p. 29, pl. 2, figs. 3 a, b.

This species differs from *B. spathulata* (Williamson) in its less tapered test and straighter sutures. It is possible that some specimens of the latter have been included in the population counts but most specimens conform closely to Seguenza's species. Specimens reported from the Mediterranean by various authors as *B. dilitata* may be referrable to *B. catanensis*. As pointed out by Marks (1951, p. 59), *B. dilitata* probably has sigmoid sutures whereas those of *B. catanensis* are almost straight.

B. catanensis is found at sixteen stations from 71—1016 m. (up to 8 %), mostly shallower than 567 m., at three stations showing displacement, and in Cores 186, 188, 192, 194—196, 198—200, but most commonly in Core 186.

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Bolivina difformis (Williamson)

(Plate 2, figure 9)

Textularia variabilis Williamson var. *difformis* Williamson, 1858, Rec. Foram. Great Britain, p. 77, pl. 6, figs. 166, 167.

The Mediterranean species is like observed specimens from the vicinity of Ireland. The species is found at five stations from 115—567 m. (up to 3 %), at two stations showing displacement, and associated with displaced faunas in Cores 188 and 191—196.

Bolivina dilitata dilitatissima Silvestri

(Plate 2, figures 5, 6, 7)

Bolivina dilitata Reuss var. *dilitatissima* Silvestri, 1893, Mem. Accad. Pont. Nuovi Lincei, vol. 9, p. 100.

It is unfortunate that Silvestri did not illustrate this form. The present identification is based on the marked resemblance of the specimens to *B. dilitata* and the greater ratio of width to length as indicated by Silvestri. They differ also from the typical form in their greater size, up to 0.58 mm. in length. It is of interest to note that Silvestri also reports *B. dilitata* from the Ionian Sea, noting that this is the species referred to *B. catanensis* by Seguenza. Specimens referred here to Silvestri's variety, however, have somewhat sigmoid sutures like those of *B. dilitata* as defined by Marks (1951, p. 59) and show a marked resemblance to observed Vienna Basin specimens. As noted previously *B. catanensis* has almost straight sutures. It appears, then, that Silvestri erred in his identification of *B. dilitata*, but, if my interpretation is correct, did not do so in relating his »variety» to that species. Specimens included in this subspecies vary greatly in the amount of limbation and raised character of the sutures, which are also occasionally slightly crenulated. An attempt was made to subdivide them according to the character of the sutures but there seemed no logical way to do so, and it is now believed that the form is a very variable one. It is found at seventeen stations from 106—1378 m. (up to 9 %), at four stations showing displacement, and in varying quantities in most of the cores, being most abundant in Core 184.

Bolivina pseudoplicata Heron-Allen and Earland

(Plate 2, figure 8)

Bolivina pseudoplicata Heron-Allen and Earland, 1930, Journ. Roy. Micr. Soc., vol. 50, p. 81, pl. 3, figs 36—40.

In the North Atlantic this species is reported shoaler than 200 m. It is found at eight stations fom 104—2760 m. (up to 50 %), at four stations showing displacement, and in most of the cores, being very common in many of them.

Bolivina subaenariensis Cushman

(Plate 2, figures 15, 16)

Bolivina subaenariensis Cushman, 1922, U. S. Nat. Mus., Bull. 104. pt. 3, p. 46, pl. 7, fig. 6.

This species is reported from the Mediterranean area by many authors as *B. aenariensis* (Costa). Pliocene specimens from near Coroncina, Italy, referred questionably to that species by Cushman (1937, p. 105), are smaller, with less limbate sutures and finer costae. If Cushman's identification is correct, the modern species should be referred to *B. subaenariensis*. If not, the possibility remains that Cushman's and Costa's species are synonymous, but a study of Costa's types will be necessary to settle this. *B. subaenariensis* is reported deeper than 114 m. in the North Atlantic. It is found at two stations from 106—143 m. (less than 1 %), at one station showing displacement, in the lower two-thirds of Core 184 (abundant), and in Cores 187 and 188 (one specimen in each).

Bulimina aculeata d'Orbigny

(Plate 2, figures 17, 18)

Polymorphium pineiformium Soldanii (pt.), 1791 Testacea, vol. 1, pt. 2, p. 118, pl. 127, fig. 1?; pl. 130, fig. vv.

Bulimina aculeata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 269, no. 7.

This species is reported in the North Atlantic from 100—2800 m. It is found at one station at 179 m. (1 %) and in Cores 189, 190, 191, 193. and 194. In some cases it occurs in great abundance, for example two occurrences of 1280 and 896 specimens in Core 189.

Bulimina costata d'Orbigny

(Plate 2, figures 19, 20)

Bulimina costata d'Orbigny, 1852, Prod. Pal. Strat. Anim. Moll. Ray., vol. 3, p. 194; Fornasini, 1901, Soc. Geol. Ital. Boll., vol. 20, p. 174, text fig. 1.

This is a very common species in the area, being found at thirty stations from 82—3241 m. (up to 16 %), at seven stations showing displacement, and in most of the cores.

Bulimina exilis Brady

(Plate 2, figure 29)

Bulimina elegans d'Orbigny var. *exilis* Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 399, pl. 50, figs. 5, 6.

This species is reported from 359—2743 m. in the North Atlantic. It is found at one station showing displacement and in occasional samples in most of the cores. In Core 186 it is very common.

Bulimina gibba Fornasini

(Plate 2, figures 21, 22)

Bulimina gibba Fornasini, 1901, Accad. Sci. Istit. Bologna Mem., ser. 5, vol. 9, p. 378, pl. 0, figs. 32, 34.

This species shows considerable variation in the number of spines ornamenting the test but all specimens have the angled lower portion of the test. The species is found at eleven stations from 71—658 m. (up to 11 %), at one station showing displacement, and in Cores 184, 186—188, 191, 192, 194, 199, and

200, in all cases apparently associated with displaced faunas except in Core 187 where displacement cannot be proved.

Bulimina marginata d'Orbigny

(Plate 2, figure 23)

Bulimina marginata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 269, no. 4, pl. 12, figs. 1—12.

This species is reported from shallow water to a depth of 2981 m. in the North Atlantic. It is found at twenty-seven stations from 82—1016 m. (up to 13 %), at all stations showing displacement, and in most of the cores in varying amounts. It is especially common in Core 184 and the lower part of Core 194, in both cases frequently associated with displaced faunas.

Globobulimina affinis (d'Orbigny)

(Plate 2, figures 24, 25)

Bulimina affinis d'Orbigny, 1839, *in* De la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foraminifères», p. 105, pl. 2, figs. 25, 26.

This species is reported from the North Atlantic deeper than 97 m. It is not found in the surface sediments but occurs in Cores 184, 186—190, 192—194, 197, 199, and 200, being especially abundant in Cores 184 and 193.

Globobulimina pseudospinescens (Emiliani)

(Plate 2, figures 26, 27)

Bulimina pyrula d'Orbigny var. *pseudospinescens* Emiliani, 1949, Riv. Ital. Pal. Strat. Milan, vol. 55, no. 1, p. 9, pl. 2, figs. 24, 25.

Emiliani places »*Bulimina pyrula* var. *spinescens* Brady» of Flint (1899) in the synonymy of his variety. Flint reports his form from off the coast of Maryland where *Globobulimina* (*Desinobulimina*) *turgidus* (Bailey) is abundant and it is probably synonymous with that species. *G. pseudospinescens* differs from *G.* (*D.*) *turgidus* (max. length 1.0+ mm.) in its smaller size (figured specimens 0.7 mm. in length), in not including specimens with a terminal aperture within its range of variation, and in having a more involute test. In the latter characteristic it more nearly approaches *G. pyrula* (d'Orbigny) but is still more involute, less ovate in shape, and larger than that species. Eastern Mediterranean specimens are slightly smaller than Emiliani's figured specimens but otherwise appear identical.

This species is found at two stations from 658—665 m. (2 %), at three stations showing displacement, and in scattered samples in Cores 184, 188, 192, 193, and 199.

Globobulimina? sp.

(Plate 2, figure 28)

This is a very fragile, thin-shelled form; complete specimens are seldom seen. It is placed tentatively in the genus *Globobulimina* although in regard to the apertural characters it more closely resembles *Virgulina*. There is no protruding tooth and the successive apertures are connected by a simple tongue attached to the apertural border.

The species is not found in the surface sediments but occurs in scattered samples in Cores 189, 190, 192—195, 198, and 200, associated with displaced faunas.

Loxostomum alatum (Seguenza)

(Plate 2, figures 30, 31, 32)

Vulvulina alata Seguenza, 1862, Atti Accad. Gioenia, Sci. Nat., ser. 2, vol. 18, p. 115, pl. 2, figs. 5, 5 a.

This species is on the borderline between *Loxostomum* and *Bolivina*. It is placed in the former for the following reasons: 1) Seguenza's figured specimens appear to have a terminal aperture; 2) specimens from the Bay of Naples where he reported it have a terminal aperture; 3) many of the eastern Mediterranean specimens have a terminal aperture. The species is found at seven stations from 205—684 m. (less than

(368)

1 %), at two stations showing displacement, and in Cores 184, 186—188, 192—194, 196, and 198—200.

Reussella spinosissima (Costa)

(Plate 2, figure 33)

Verneuilina spinosissima Costa, 1856, Atti Accad. Pont., vol. 7, pt. 2, p. 263, pl. 23, figs. 5 a—c.

This species is found at eleven stations from bay—117 m. (up to 4 %), at 3309 m., at one station showing displacement, and in one sample in Core 188 and two in Core 194, associated with displaced faunas.

Robertina translucens Cushman and Parker

(Plate 2, figure 34)

Robertina translucens Cushman and Parker, 1936, Contr. Cushman Lab. Foram. Res., vol. 12, pt. 4, p. 99, pl. 16, figs. 8 a, b.

Robertina is included in the Buliminidae with some hesitation. The genus seems to be related to genera in several families depending on which characteristics are emphasized.[1] *R. translucens* is found at fourteen stations from 179—1265 m. and 3241 m. (up to 3 %), at five stations showing displacement, and in varying abundance in all the cores except Cores 184 and 200.

Uvigerina auberiana d'Orbigny

(Plate 2, figures 35, 36)

Uvigerina auberiana d'Orbigny, 1839, *in* De la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foraminifères», p. 106, pl. 2, figs. 23, 24.

Mediterranean specimens are similar to those of the smaller size-group found in the North Atlantic by Phleger *et al.* (1953, p. 37). The species is found at fifteen stations from 179—731 m. and 1265 m. (up to 9 %), at four stations showing displacement, and in Cores 191, 192, 194, and 200 associated with displaced faunas.

Uvigerina mediterranea Hofker

(Plate 2, figures 39, 40)

Uvigerina mediterranea Hofker, 1932, Publ. Staz. Zool. Napoli, vol. 12, fasc. 1, p. 118, text figs. 32 a—g.

U. finisterrensis Colom (1952, p. 27, text fig. 4, pl. 4, figs. 1, 2, 13, 14) may be a synonym of Hofker's species. Eastern Mediterranean specimens show considerable variation in size of tests and coarseness of costae. The specimens all appear to belong to the same taxon and most of them are similar to those described by Hofker. The species is one of the most common in the surface sediments. It is found at thirty-seven stations from 82—3241 m. (up to 48 %), at six stations showing displacement, in Core 184 (abundantly), and in scattered samples in Cores 188, 189, 192, and 199. In all the core samples studied, except Core 189, it is associated with displaced faunas which seems strange in view of its deep depth occurrence in surface sediments.

Uvigerina peregrina Cushman

(Plate 2, figures 37, 38).

Uvigerina peregrina Cushman, 1923, U. S. Nat. Mus., Bull. 104, pt. 4, p. 166. pl. 42, figs. 7—10.

Eastern Mediterranean specimens are somewhat smaller (max. length *ca.* 0.68 mm.) than those described by Cushman (max. length 0.85 mm.), but are otherwise very similar to topotype specimens. The species is reported in the North Atlantic deeper than 29 m. (usually much deeper) by Cushman and deeper than 610 m. off the northeastern United States by Parker (1948). It is found at one station at 1016 m. (4 %), at two stations showing displacement, and in Cores 184, 186, 188, 191—194, and 199.

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[1] This species is referred to *Robertina* for reasons previously published (Parker, 1952, p. 416).

Family SPIRILLINIDAE

Patellina corrugata Williamson

Patellina corrugata Williamson, 1858, Rec. Foram. Great Britain, p. 46, pl. 3, figs. 86—89.

This species is widely reported from all depths in the North Atlantic. It is found at three stations from 567—1378 m. (up to 2 %), at three stations showing displacement, and in scattered samples in Cores 184, 187—189, and 191—196.

Spirillina vivipara Ehrenberg

(Plate 3, figure 4)

Spirillina vivipara Ehrenberg, 1841, Abh. k. Akad. Wiss. Berlin, p. 422, pl. 3, sec. 7, fig. 41.

This species has been reported in the North Atlantic to a depth of 366 m. It is found at thirteen stations from 71—996 m. (up to 3 %), at six stations showing displacement, and in scattered samples in Cores 184, 188, 192, 194, and 196, associated with displaced faunas.

Spirillina wrightii Heron-Allen and Earland

(Plate 3, figures 1, 2, 3)

Spirillina wrightii Heron-Allen and Earland, 1930, Journ. Roy. Micr. Soc., vol. 50, p. 181, pl. 4, figs. 54—58.

This species is referred by Cushman (1931, p. 81, pl. 2, figs. 4, 5) to *S. limbata* Brady var. *denticulata* Brady. Cushman says that Brady did not »mention» the difference of the two sides, but it seems very unlikely that he would have ignored such a feature. For this reason the species with the tubercles on the ventral side is referred here to *S. wrightii*. A study of Brady's types would settle this question. The species is found at four stations from 75—143 m. (up to 3 %), at two stations showing displacement, and in one sample in Core 194 associated with a displaced fauna.

Family DISCORBIDAE

Asterigerinata mamilla (Williamson)

(Plate 3, figures 5, 6)

Rotalina mamilla Williamson, 1858, Rec. Foram, Great Britain, p. 54, pl. 4, figs. 109—111.

This species has been reported from shallow water. Phleger *et al.* (1953) report it (as *Discorbis mamilla*) from displaced faunas in the North Atlantic cores. It is found at twelve stations, mostly in the Aegean Sea, from bay-179 m. (up to 30 %), at three stations showing displacement, and associated with displaced faunas in Cores 186, 187, 194, and 195.

Eponides repandus (Fichtel and Moll)

Nautilus repandus Fichtel and Moll, 1798, Test. Micr., p. 35, pl. 3, figd. a—d.

This species is reported from the North Atlantic shallower than 170 m. It is found at nine stations from 51—567 m. (up to 4 %) but does not occur in the core samples studied.

Gavelinopsis praegeri (Heron-Allen and Earland)

(Plate 3, figures 24, 25)

Discorbina praegeri Heron-Allen and Earland, 1913, Proc. Roy. Irish Acad., vol. 31, pt. 64, p. 122, pl. 10, figs. 8—10.

G. translucens (Phleger and Parker) (*Rotalia translucens* Phleger and Parker, 1951) is occasionally included in the population counts of the core faunas. It differs from *G. praegeri* in being plano-convex while the latter is convexo-concave or flat on the ventral side. This difference is very apparent when comparing specimens of *G. praegeri* from the British Isles and *G. translucens* from the Gulf of Mexico; near the former only *G. praegeri* occurs, in the latter only *G. translucens*. In the eastern Mediterranean surface sediments only *G. praegeri* is found but both species occur in the cores, sometimes concurrently. When this happens they are difficult to separate in rapid routine counting of populations. It is interesting to speculate on the possibility of the two species in the cores belonging to the same taxon which has since developed along different lines in the Recent Mediterranean and other areas. In North Atlantic cores collected by the Swedish Deep-Sea Expedition, *G. praegeri* was reported in Core 290 north of Latitude 40° N, while *G. translucens* occurred in Cores 228 and 252 south of Latitude 16° N (Phleger, *et al.*, 1953). *G. praegeri* s. s. is found at twenty-four stations from 71—1265 m. (up to 5 %) and at five stations showing displacement. Both species (or sometimes *G. praegeri* only) occur in varying abundances in all cores except Cores 197—200.

Gyroidina altiformis R. E. and K. C. Stewart

(Plate 3, figures 10, 11, 12)

Gyroidina soldanii d'Orbigny var. *altiformis* R. E. and K. C. Stewart, 1930, Journ. Pal., vol. 4, no. 1, p. 67, pl. 9, fig. 2.

This species does not appear to be related to *G. soldanii* (*vide G.* cf. *G. neosoldanii*) since it has oblique rather than radial sutures. It is found at thirty-four stations from 201—2442 m. (up to 34 %), at seven stations showing displacement, and in Cores 184, 186, 192, 193, 197 (?), and 199, being found in abundance only in Core 184.

Gyroidina delicata Parker, n. sp.

(Plate 3, figures 7, 8, 9)

Test relatively small for the genus, plano-convex or with the central part of the dorsal side sometimes protruding slightly, consisting of about three whorls, umbilicus closed, upper edge of the periphery rather sharply angled, usually slightly lobulate; chambers 6—8 (occasionally 9) in the final whorl; sutures distinct, narrow, oblique, slightly depressed on the dorsal side, on the ventral side slightly curved, slightly depressed; wall comparatively thin, slightly translucent, densely perforate with very fine pores; aperture extending from the umbilicus to about three-fourths of the way to the periphery, with a narrow lip. Maximum diameter 0.4 mm. (most specimens smaller); maximum thickness 0.25 mm.

The holotype (U. S. N. M. P6340) and figured paratypes (U. S. N. M. P6341 a, b) are from Core 193, no. 57, 549.5—550 cm. from the top, Lat. 34° 12′ N, Long. 0° 24.22′ E, at a depth of 2130 m.

This species differs from *G. altiformis* in its smaller size, less acute periphery, lack of a deep open umbilicus, and more depressed sutures (except on dorsal side, final whorl of *G. altiformis*). In the adult specimens on the dorsal side the final chambers are sometimes slightly tipped inward and back so that the previous chambers jut above. This feature is also seen in *G. altiformis*, which also often has limbate sutures although this seems to be a variable characteristic. Specimens referred by Parker (1954, pl. 7, figs. 9, 10) to *G. neosoldanii* Brotzen are very similar though larger; this is also true of part of the specimens referred to *G. soldanii* d'Orbigny vars. by Phleger, *et al.* (1953).

G. delicata is not found in the surface sediments but occurs in all the cores except Cores 184 and 199. The highest occurrence is in Core 196 at 59.5 cm. but usually it does not appear until much deeper in the section.

Gyroidina cf. **G. neosoldanii** Brotzen

(Plate 3, figures 13, 14, 15, 16, 17, 18)

Gyroidina orbicularis Phleger, Parker, and Peirson, 1953 (not d'Orbigny, 1826), Rep'ts. Swedish Deep-Sea Exped., vol. 7, no. 1, p. 41, pl. 8, figs. 35, 36.

Brotzen (1936, p. 158) renamed Brady's (1884, p. 706, pl. 107, figs. 6, 7) »*Rotalia soldanii* d'Orbigny». Brady's figured specimens, however, appear to represent two species: fig. 6, with oblique sutures; fig. 7, with radiate sutures. The former somewhat resembles *G. delicata* Parker, n. sp., but appears to be a much larger heavier form; the latter resembles the Mediterranean specimens considered here (max.

		G. orbicularis	*G. soldanii*	*G.* cf. *G. neosoldanii*
max. size:	diameter	0.68 mm.	0.56 mm.	0.54 mm.
	thickness	0.50 mm.	0.40 mm.	0.36 mm.
no. of whorls		2—1/2	3	3
character of whorls		broad	narrow	medium, outer one of large forms narrow
umbilicus		closed	open	closed except in large forms when the opening is small and deep
sutures		radiate	radiate	radiate
spiral suture		flush	outer whorl channeled	outer whorl of large specimens channeled

diam. 0.54 mm.) although it is somewhat larger (0.72 mm.) and seems to have a more rounded periphery. As previously mentioned (*vide G. delicata*) the specimens from the eastern Gulf of Mexico referred by Parker (1954, p. 528, pl. 9, figs. 9, 10) to *G. neosoldanii* have oblique sutures. A study of various species of the genus *Gyroidina* leads me to believe that the angle of the sutures is not a variable feature and is, therefore, important in specific diagnosis. Before the characteristics of *G. neosoldanii* can be precisely defined it will be necessary to study Brady's figured specimens and to designate a type for the species. It seem unwise to do so from a review of the figures. Designations of this kind have frequently been made from figured specimens but the practice is a dangerous one and often leads to worse confusion. Specimens referred by various authors to *G. orbicularis*, and to a somewhat less extent to *G. soldanii*, in the Mediterranean, North Atlantic, and Gulf of Mexico are similar to Brady's fig. 7, and to the specimens here referred tentatively to *G. neosoldanii*. Topotypes from Rimini, Italy, apparently referrable to d'Orbigny's two species (*orbicularis*, *soldanii*) are unlike anything I have seen in the Mediterranean samples and are probably derived from nearby fossil localities. The following table shows the characteristics of the various forms:

From this table it appears that the Recent Mediterranean species is closer to *G. soldanii* than *G. orbicularis*. The Mediterranean specimens fall roughly into two groups. One group (pl. 3, figs. 16, 17, 18) contains smaller, more compressed specimens and is the one most frequently referred by authors to *G. orbicularis* since it does not show channeling of the spiral suture. (It differs from that species in its small size, greater compression (ratio of diameter to thickness nearly 2: 1)) and increased number of whorls). The great difficulty, however, of consistently separating these small specimens from the larger ones leads to the belief that they belong to the same taxon.

It is of interest to note that the specimens referred by Phleger, *et al.* (1953) to »*G. soldanii* variants» have oblique sutures and are therefore not referrable to that species.

G. cf. *G. neosoldanii* is found at thirty-six stations from 106—2738 m. (up to 82 %) mostly deeper than 200 m. and with the highest frequencies deeper than about 650 m., at five stations showing displacement, and in varying abundances in all the cores expect Cores 195 and 198.

Gyroidina umbonata (Silvestri)

(Plate 3, figures 19, 20)

Rotalia soldanii d'Orbigny var. *umbonata* Silvestri, 1898, Mem. Accad. Pont. Nuovi Lincei, vol. 15, p. 329, pl. 6, figs. 14 a—c.

This species is found at fifteen stations from 205—1016 m. (up to 2 %), at four stations showing displacement, and in scattered samples in Cores 184, 186, 188, 192, 194, 196, and 200, usually associated with displaced faunas.

Hanzawaia rhodiensis (Terquem)

(Plate 3, figures 21, 22, 23)

Truncatulina rhodiensis Terquem, 1878, Mém. Soc. Géol. France, ser. 3, vol. 1, pt. 3, p. 21, pl. 1, fig. 26.

This genus is placed in the Discorbidae since its closest affiliation appears to be with *Rosalina*. The genera *Hanzawaia* Asano 1944 and *Cibicidina* Bandy 1949 are considered to be synonymous since the »supplementary lobes» in the umbilical area of the type species of the former are present, though to a lesser degree, in the latter. This differential development of the »supplementary lobes» does not seem a sufficient basis for generic differentiation. *H. rhodiensis* is found at twenty-five stations from 51—1378 m. (up to 7 %) with the greatest abundance from 51—106 m., at six stations showing displacement and in Cores 186, 188, 191—195, 199, and 200, in scattered samples associated with displaced faunas.

Neoconorbina terquemi (Rzehak)

(Plate 3, figures 26, 27)

Rosalina orbicularis Terquem, 1876 (not *R. orbicularis* d'Orbigny, 1850), Anim. sur la Plage de Dunkerque, p. 75, pl. 9, figs. 4 a, b.

Discorbina terquemi Rzehak, 1888, Austria, Geol. Reichs., Verh., p. 228.

This species is found at twenty stations from bay—799 m. (up to 7 %) with the highest frequencies shallower than 117 m., at six stations showing displacement, and in Cores 188, 191—197, 199, and 200, often associated with displaced faunas.

Neoconorbina williamsoni (Parr)

(Plate 3, figures 28, 29)

Rotalina nitida Williamson, 1858, Rec. Foram. Great Britain, p. 54, pl. 4, figs. 106—108.

Discorbis williamsoni Parr, 1932, Proc. Roy. Soc. Victoria, vol. 44 (n. s.), pt. 2, p. 226, pl. 21, fig. 25.

This species is found at two stations from 117—179 m. (less than 1 %), at three stations showing displacement, and in Cores 184, 188, 190—196, 198, 199, and 200, mostly associated with displaced faunas.

Pseudoeponides umbonatus (Reuss) var.

(Plate 3, figures 30, 31, 32)

Eponides umbonatus (Reuss) and variants, Phleger, Parker, and Peirson, 1953 (part), Rep'ts. Swedish Deep-Sea Exped., vol. 7, no. 1, p. 42, pl. 9, figs. 9, 10.

The variant figured by Phleger *et al.* is identical to the Mediterranean form. Typical specimens of *P. umbonatus*, having a subacute periphery, were not observed. A comparison of the Mediterranean variant with Reuss's specimens might show that it is a different species. It does not occur in the surface sediments but is found in varying abundances in all the cores except Cores 184, 195, 196, and 200. With three exceptions (Core 193, 9.5 cm.; 197, 149.5 cm.; 191, 279.5 cm.) it occurs deeper than 350 cm. in the core sections.

Rosalina aff. R. columbiensis (Cushman)

(Plate 3, figures 35, 36)

This is one of the most common species of *Rosalina* in the Mediterranean samples, especially in the displaced faunas of the cores. It may be referrable to several (synonymous) species described from this area but on account of the lack of adequate illustrations and descriptions of these a precise designation cannot be given without reviewing the types. The species is very similar to *R. columbiensis* (Cushman, 1925, p. 43, pl. 6, fig. 13 — *Discorbis*) but differs from it in the more sharply angled periphery and less inflated chambers. Specimens are found at eight stations from 51—201 m., 338 m., and 3499 m. (up to 1 %, 33 % at

3499 m.) and at all stations showing displacement. It occurs in Cores 188, 191—196, and 199 (most abundantly in Cores 192, 194), in all cases associated with displaced faunas.

Rosalina globularis bradyi (Cushman)

(Plate 3, figures 37, 38)

Discorbis globularis d'Orbigny var. *bradyi* Cushman, 1915, U. S. Nat. Mus. Bull. 71, pt. 5, p. 12, pl. 8, fig. 1.

Mediterranean specimens are identical to Cushman's types. Whether or not this form is related to *R. globularis* is difficult to tell. In discussing the identity of *R. globularis* with various workers on the Foraminifera, I have encountered no unanimity of opinion. Some believe that Cushman's variety is *R. globularis* s. s., but it differs from d'Orbigny's illustrations of this species in having a narrow keel, being finely perforate on the ventral side, and in usually having non-depressed, limbate sutures on the dorsal side. Specimens from the vicinity of Ireland appear close to d'Orbigny's figured species except that they, too, have a finely perforate ventral side. Associated with these, and apparently a variant form, are specimens referrable to Cushman's variety. If, therefore, an examination of d'Orbigny's types reveals a form with a finely perforate ventral side it may be that Cushman's variety is in reality a variant form of *R. globularis* and is, therefore, synonymous with it. All the Mediterranean specimens seem to be referrable to the keeled form.

R. globularis bradyi is found at seven stations from bay—143 m. (up to 1 %), at two stations showing displacement, and in Cores 188, 192, 194—196, and 200, in scattered samples associated with displaced faunas.

Rosalina obtusa d'Orbigny

(Plate 3, figures 33, 34, 39)

Rosalina obtusa d'Orbigny, 1846, Foram. Foss. Bass. Tert. Vienne, p. 179, pl. 11, figs. 4—6.

This species is found at twenty stations from bay—996 m. (up to 9 %) mostly shoaler than 338 m., at four stations showing displacement, and in scattered samples in Cores 187, 188, 191—196, 199, and 200, associated with displaced faunas.

Rosalina suezensis (Said)

(Plate 3, figures 40, 41)

Discorbis suezensis Said, 1949, Cushman Lab. Foram. Res., Spec. Publ. 26, p. 36, pl. 3, fig. 34.

The Mediterranean specimens are identical to Said's holotype and topotypes. The species is reported in the North Atlantic shallower than 850 m. It is found at nine stations from 71—567 m. (up to 1 %) mostly shallower than 256 m., at two stations showing displacement, and in Cores 192 and 200 associated with displaced faunas.

Rosalina spp.

There are many species of *Rosalina* in the surface sediments and cores which have not been differentiated because of their rare occurrence. The genus appears to be almost always confined to depths of less than 1000 m., in most cases considerably less. For this reason *Rosalina* spp. in the cores are interpreted as having been displaced from relatively shallow water. This is usually substantiated by the presence of known shallow species. *Rosalina* spp. are found at three stations from 51—115 m. (up to 1 %), at one station showing displacement, and in Cores 188, 191, 192, 194—196, and 200, associated with displaced faunas, being very abundant in Cores 192 and 194.

Valvulineria complanata (d'Orbigny)

(Plate 3, figures 42, 43, 44)

Rosalina complanata d'Orbigny, 1846, Foram. Foss. Bass. Tert. Vienne, p. 175, pl. 10, figs. 13—15.

? *Discorbina bradyana* Fornasini, 1900, Mem. R. Accad. Sci. Istit. Bologna, ser. 5, vol. 8 (1899—1900), p. 393, text fig. 43.

Mediterranean specimens are identical with those seen from the Miocene of Baden, Austria. Writers on Mediterranean Foraminifera refer similar specimens to *V. bradyana* and this species may be synonymous although Fornasini's figured specimens are not identical. *V. complanata* is found in thirteen stations from 51—799 m. (up to 2 %), and in Cores 184, 188—190, 192, 194, 197, 199, and 200.

Family ROTALIIDAE

Rotalia granulata (di Napoli Alliata)

(Plate 4, figures 1, 2)

Eponides frigidus Cushman var. *granulatus* di Napoli Alliata, 1952, Riv. Ital. Pal. Strat., vol. 58, no. 3, p. 9, pl. 5, figs. 3, 3 a, 3 b.

Eastern Mediterranean specimens resemble topotypes from the yellow sands of the upper Pliocene Castell' Arquato, Italy. They differ somewhat in being more convex on the ventral side. The tests have a thick, narrow keel and the umbilical region is filled with a mass of pillars of various sizes and shapes.

The species is found at eight stations from bay—143 m. (up to 4 %) and occurs rarely in Core 200.

Streblus beccarii (Linné) and vars.

»*Cornu hammonis*» Plancus, 1739, Conch, Min., p. 8, pl. 1, fig. 1.

»*Ammonia unita*» Gualtieri, 1742, Index Test., pl. 19, figs. H, I.

Nautilus beccarii Linné, 1767, Syst. Nat., ed. 12, p. 1162.

The generic name *Streblus* Fischer 1817 has been used here with some trepidation, since I am by no means sure that it is the correct one. There appears to be good evidence that *Ammonia* Brunnich 1771 has priority. Since, however, the available information is at second hand (*vide* Frizzell and Keen, 1949; Smout, 1954) this name has not been used here. Specimens from Rimini, Italy, show considerable variation in the amount of limbation of sutures, presence or character of ventral plugs, and number of chambers in the last-formed whorl. It is possible that more than one species is included in the group, though specimens referred to *S. beccarii* in various parts of the world show a similar type of variation. Some of these have been named but perhaps such formal differentiation will prove biologically unsound. The naming of varieties, or infrasubspecies, is often defended by the paleontologist since it has a useful purpose in stratigraphic work but in most cases the forms so named are in reality species or subspecies and not in any sense varieties. In the present case there is no good reason for differentiation, either biologically, stratigraphically, or apparently ecologically. The species is found at seven stations from bay—179 m. (up to 7 %), at three stations showing displacement, and in scattered samples in Cores 184, 188, 192, 194, 196, and 198, associated with displaced faunas.

Family ELPHIDIIDAE

Elphidium advena (Cushman)

(Plate 4, figures 3, 4)

Polystomella advena Cushman, 1922, Publ. 311, Carnegie Instit. Washington, p. 56, pl. 9, figs. 11, 12.

Specimens are larger (max. diam. 0.8 mm.) than those described by Cushman (max. diam. 0.5 mm.). The species is reported in »shallow» water in the North Atlantic and shallower than 115 m. in the eastern Gulf of Mexico. It is found at nine stations from bay—179 m. (up to 2 %) and occurs in Cores 184, 191, 192, 194, 195, 199, and 200, associated with displaced faunas.

Elphidium complanatum (d'Orbigny)

(Plate 4, figure 5)

Polystomella complanata d'Orbigny, 1839, *in* Barker-Webb and Berthelot, Hist. Nat. Iles Canaries, vol. 2, pt. 2, »Foraminifères», p. 129, pl. 2, figs. 35, 36.

This species is reported by Colom (1950, 1952) shallower than 726 m. off the coast of Africa and 105 m. off the coast of Galicia. It is found at thirteen stations from bay—205 m. (up to 7 %) and occurs in Cores 188, 192—194, and 196, associated with displaced faunas.

Elphidium crispum (Linné)

»*Cornu hammonis*» etc., Plancus, 1739, Conch. Min., p. 10, pl. 1, figs. 2 d—f.

»*Nautilus minimus*» etc. Gualtieri, 1742, Index Test. Conch., pl. 19, figs. A, D.

Nautilus crispus Linné, 1758, Syst. Nat., ed. 10, vol. 1, p. 709.

Nautilus macellus Fichtel and Moll, Testacea microscopica, p. 66, var. B, pl. 10, figs. h—k, 1798.

Elphidium nigarense Cushman, 1936, Contr. Cushman Lab. Foram. Res., vol. 12, p. 85, pl. 15, figs. 3 a, b.

This species is very variable. Mediterranean specimens have been subdivided by Cushman (1939) and others, part being referred to *E. macellum*. There seems no logical way to do this since there is a complete series of variations in number of chambers, compression of test, character of umbo, etc. A study was made of specimens from Rimini, Italy, presumably the type locality of *E. crispum* (Cushman, 1939, p. 51). The beach sands at Rimini seems to contain a mixture of Recent forms and fossil forms derived from nearby Pliocene and Pleisticene outcrops. For this reason it may contain species of *Elphidium* from different sources. Since, however, a similar amount of variation, though on a smaller scale, has been observed in other Recent Mediterranean samples, the two species, *crispum* and *macellum*, are believed to be synonymous. Also included in the population counts of *E. crispum* are specimens referrable to *E. nigarense* whose only claim to distinction is a lesser number of chambers than is typically present. Such specimens also occur in the Rimini complex. *E. crispum* is reported by Colom (1950) off the coast of Africa to a depth of 726 m. It is found at fourteen stations from bay—338 m. (up to 7 %), at two stations showing displacement, and in Cores 192, 194, 196, 198, and 199, associated with displaced faunas.

Elphidium granosum (d'Orbigny)

(Plate 4, figures 10, 11)

Nonionina granosa d'Orbigny, 1846, Foram. Foss. Bass. Tert. Vienne, p. 110, pl. 5, figs. 19. 20.

Elphidium lidoense Cushman, 1936, Contr. Cushman Lab. Foram. Res., vol. 12, pt. 4, p. 86, pl. 15, figs. 6 a, b.

Mediterranean specimens are similar to those from Miocene of the Vienna Basin except that they are smaller (max. diam. 0.43 mm.). The types of Cushman's species, *E. lidoense*, are identical. *E. granosum* may be the species referred by some workers in the Mediterranean area to *E. decipiens* (Costa), whose original figure shows a keeled test with 13 chambers in the final whorl. For a comparison of *E. granosum* with *E. minimum* (Seguenza) see the discussion of the latter species. According to Bramlette (personal communication) *E. granosum* has a radiate wall structure. This species is found at nine stations from 51—201 m. (up to 6 %), mostly shoaler than 106 m., and in Cores 192 and 199 associated with displaced faunas.

Elphidium cf. **E. minimum** (Seguenza)

(Plate 4, figures 8, 9)

The Recent specimens appear to have a less acutely angled periphery than Seguenza's (1880, p. 333, pl. 17, figs. 38, 38 a — *Polystomella*) figured specimen. They resemble *E. granosum* but have non-depressed sutures, and, therefore, a non-lobulate periphery and in most cases a simple rather than multiple umbo. According to Bramlette (personal communication) the wall has a radiate structure. This species is found at nine stations from bay-179 m. (up to 5 %), at three stations showing displacement, and in Cores 186, 188, 194, and 196, in occasional samples associated with displaced faunas.

Elphidium pulvereum Todd

(Plate 4, figure 6)

Elphidium pulvereum Todd, 1958, Rep'ts. Swedish Deep-Sea Exped., vol. VIII, no. 3, p. 201, pl. 1, figs. 19, 20.

Eastern Mediterranean specimens are identical with l. cestern Mediterranean specimens kindly sent me by Miss Ruth Todd. The species is found at three stations from 106—201 m. (less than 1 %), at three stations showing displacement, and in Cores 188, 190—196, 198, and 199, associated with displaced faunas. The most frequent occurrences are in Cores 192, 194 and 195; in the other cores they are scattered.

Elphidium spp.

Elphidium spp. includes all undesignated species found in the present study. Most of these occur so rarely that it would be impractical to list them separately. Since the genus has, without exception, a shallow distribution its occurrence even as a unit is valuable. In a core it denotes the presence of displaced shallow material. *Elphidium* spp. are found at one station at 287 m. (0.3 %), at one station showing displacement, and in Cores 184, 188, 191—198, and 200, associated with displaced faunas.

Parrellina verriculata (Brady)

(Plate 4, figure 7)

Polystomella verriculata Brady, 1881, Quart. Journ. Micr. Sci., vol. 21, p. 66; 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 738, pl. 110, figs. 12 a, b.

This species is incorrectly listed as *Elphidium verriculatum* in Tables 3 and 15. Tt is found at twelve stations from 51—201 m. (up to 3 %), at one station showing displacement, and in Cores 192, 194, and 195 associated with displaced faunas.

Family CASSIDULINIDAE

Cassidulina carinata Silvestri

(Plate 4, figure 15)

Cassidulina laevigata d'Orbigny var. *carinata* Silvestri, 1896, Accad. Pont. Nuovi Lincei, Mem. 12, p. 104, pl. 2, fig. 10 (*C. laevigata* in expl. of pl.).

This is a common species in the area being found at twenty-five stations from 51—996 m. (up to 14 %) with relatively high frequencies to a depth of 567 m., at six stations showing displacement, and in all the cores except Core 197.

Cassidulina crassa d'Orbigny

(Plate 4, figure 12)

Cassidulina crassa d'Orbigny, 1839, Voy. Amér. Mérid., vol. 5, pt. 5, »Foraminifères», p. 56, pl. 7 figs. 18—20; Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 429, pl. 54, fig. 5.

Brady's interpretation of this species is the one followed here. It is found at twenty-six stations from 104—1378 m. (up to 7 %), at six stations showing displacement, and in

Cores 184, 186, 188, 191, 192, 194—197, 199, and 200, being most common in Cores 192 and 194.

Cassidulina cf. **C. oblonga** Reuss

(Plate 4, figure 14)

Marks (1952) says that Reuss's (1850, p. 376, pl. 48, figs. 5, 6) species is probably synonymous with *C. crassa* (d'Orbigny). Inasmuch as Brady's interpretation of *C. crassa* is followed here the present species is tentatively referred to *C. oblonga*. Mediterranean specimens are larger than those described by Reuss, reaching a length of *ca.* 0.36 mm., and the sutures are non-depressed. Similar specimens from the Miocene of Baden in the Vienna Basin, presumably referrable to *C. oblonga*, are about the same size as the Recent form but have a larger tooth.

The species is found at twenty-three stations from 51—996 m. (up to 9 %) mostly shallower than 384 m., at six stations showing displacement, and in Cores 184, 187, 188, 191, 192, 194, 195, 197, 199, and 200, mostly associated with displaced faunas (exceptions are occasional single specimens).

Cassidulina cf. **C. sicula** Seguenza

(Plate 4, figures 16, 17)

Mediterranean specimens are smaller (max. diam. 0.3 mm.) than Seguenza's (1862, pp. 111, 125, pl. 1, figs. 7, 7 a) (0.6 mm.). In other respects they are similar. The most outstanding characteristic of the species is the lobulation of the periphery, an unusual feature in a keeled form. It is not found in the surface sediments but occurs in varying abundance in all the cores except Cores 184 and 198.

Cassidulina subglobosa Brady

(Plate 4, figure 13)

Cassidulina subglobosa Brady, 1881, Quart. Journ. Micr. Sci., vol. 21, pl. 30 (60); 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 430, pl. 54, figs. 17 a—c.

This species does not reach a very large size in Mediterranean samples, the maximum diameter being about 0.36 mm. It has been widely reported from the North Atlantic at all depths to 5532 m. It is found at ten stations from 179—1016 m. (up to 2 %), at two stations showing displacement, and in Cores 191—194, 197, and 200, mostly associated with displaced faunas.

Cassidulinoides tenuis Phleger and Parker

(Plate 4, figures 18, 19)

Cassidulinoides tenuis Phleger and Parker, 1951, Geol. Soc. America, Mem. 46, pt. 2, p. 27, pl. 14, figs. 14 a, b, 15—17.

Mediterranean specimens are identical with those from the Gulf of Mexico, reported chiefly from 255—1100 m. In view of this it seems strange that the species has not been observed in the North Atlantic. It is not found in the surface sediments but occurs in Cores 186, 189—198, usually rarely but occasionally in great abundance.

Virgulina complanata Egger

(Plate 4, figure 20)

Virgulina schreibersiana Czjzek var. *complanata* Egger, 1893, Abhandl. k. bay. Akad. Wiss. München, Cl. II, vol. 18, p. 292, pl. 8, figs. 91, 92.

This species is found at one station at 3974 m. (13 %), and in Cores 193, 194, and 197, being very abundant in the lower part of Core 193.

Virgulina mexicana Cushman

(Plate 4, figures 26, 27)

Virgulina mexicana Cushman, 1922, U. S. Nat. Mus., Bull. 104, pt. 3, p. 120, pl. 23, fig. 8.

This species is found at one station at 3974 m. (61 %), at one station showing displacement, and in scattered samples in all the cores except Cores 189, 191, and 197.

Family EPISTOMINIDAE

Epistominella rugosa convexa Parker, n. subsp.

(Plate 4, figures 21, 22, 23)

This subspecies may be distinguished from the typical form by its more convex dorsal side, larger umbo, and less rugose wall especially on the dorsal side. It differs from *E. umbonifera* (Cushman) in having a keel. Maximum diameter 0.32 mm., thickness 0.18 mm.

The holotype (U. S. N. M. P6125) and figured paratypes (U. S. N. M. P6126 a, b) are from ATLANTIS Sta. 4723, Lat. 37° 11′ N, Long. 11° 33.5′ E, at a depth of 567 m.

Although this form appears to be closely related to *E. rugosa*, reported from deeper than 250 m. in the Gulf of Mexico, neither form has been observed in the North Atlantic. *E. rugosa convexa* is found at ten stations from 541—1016 m. (up to 13 %) with highest frequencies from 600—700 m., at two stations showing displacement, and in Cores 186—189, 192, 194, 196 and 199 very occasionally except in Cores 186, 192, and 194 where it is more common.

Siphonina reticulata (Czjzek)

(Plate 4, figure 25)

Rotalina reticulata Czjzek, 1848, Haidinger's Nat. Abhandl., vol. 2, p. 9, pl. 13, figs. 7—9.

This species is found at twenty-one stations from 104—1016 m. (up to 3 %), at three stations showing displacement, and in Cores 194 and 199 (once in each) associated with displaced faunas.

Family CHILOSTOMELLIDAE

Chilostomella mediterranensis Cushman and Todd

(Plate 4, figure 24)

Chilostomella mediterranensis Cushman and Todd, 1949, Contr. Cushman Lab. Foram. Res., vol. 25, pt. 4, p. 92, pl. 15, figs. 25, 26.

This species is found at six stations from 567—1378 m. (up to 2 %), at three stations showing displacement, and in varying abundance in all the cores.

Pullenia bulloides (d'Orbigny)

Nonionina bulloides d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 293, no. 2; 1846, Foram. Foss. Bass. Tert. Vienne, p. 107, pl. 5, figs. 9, 10.

This species is not found in the surface sediments but occurs in scattered samples in Cores 186, 189, 192, 193, 197, and 199.

Pullenia quinqueloba (Reuss)

(Plate 4, figures 32, 33)

Nonionina quinqueloba Reuss, 1851, Zeitschr. deutsch. Geol. Ges., vol. 3, p. 71, pl. 5, fig. 31.

Specimens have four or five chambers in the final whorl, but are otherwise identical. The species is reported from the North Atlantic deeper than 80 m. It is found at fourteen stations from 82—1265 m. (up to 3 %), at three stations showing displacement, and in Cores 184, 188, 191—194, 196, 198, and 200, associated with displaced faunas. This association in the cores seems rather strange in view of the fact that this has always been considered a deep-living species.

Pullenia cf. **P. riveroi** Bermudez

(Plate 4, figure 31)

As in the case of North Atlantic specimens reported by Phleger *et al.* (1953, p. 47) the Mediterranean specimens most closely resemble that shown by Bermudez (1939, p. 11, pl. 2, figs. 1—6) in his figure 4. The species is not found in the surface sediments but occurs in Cores 184, 188—195, 198, and 199.

(379)

Rotamorphina? involuta Parker, n. sp.

(Plate 4, figures 28, 29, 30)

Test of medium size, with rounded periphery, slightly trochoid, almost entirely involute; chambers 5—6 in the final whorl; sutures narrow, slightly curved, slightly depressed; wall smooth, thin, often translucent, with very fine, dense perforations; aperture extending from the umbilicus on the ventral side over onto the dorsal side, with a small ventral flap; maximum length 0.39 mm., width 0.32 mm., thickness 0.18 mm.

The holotype (U. S. N. M. P6127) and figured paratypes (U. S. N. M. P6128 a, b) are from ATLANTIS Sta. 4714, Lat. 32° 30′ N., Long. 15° 49′ E., at a depth of 665 m.

This species has been placed tentatively in the genus *Rotamorphina*. It seems to bear somewhat the same relation to that genus that *Allomorphinella* does to *Allomorphina* except that the involution is not complete. It differs from other species of *Rotamorphina* in the partially involute character and in the aperture which extends over onto the side. It differs from *R. laevigata* (Phleger and Parker) in both these respects, in being more compressed and less circular in outline, and in having the small ventral flap cling more closely to the test.

This species is found at eight stations from 567—996 m. (up to 5 %), at three stations showing displacement, and in Cores 187, 192, 194, and 195, in scattered samples associated with displaced faunas.

Sphaeroidina bulloides d'Orbigny

Sphaeroidina bulloides d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 267, no 1; Modèles, no. 65.

This species is reported from off the northeastern United States deeper than 80 m. (Parker, 1948) and from off Galicia deeper than 215 m. (Colom, 1952). It is found at twenty four stations from 75—1265 m. (up to 4 %), at six stations showing displacement, and in scattered samples in Cores 184, 188, 192, 194, and 200, associated with displaced faunas.

Family CERATOBULIMINIDAE

Höglundina elegans (d'Orbigny)

»*Hammoniformis trochiformis*» Soldani, 1789—1799, Test., app., pl. 2, fig. R.

Rotalia (*Turbulina*) *elegans* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 276, no. 54, (not *Rotalia elegans*, *op. cit.*, p. 272, no. 6).

This species is reported deeper than 42 m. in the North Atlantic. It is found at sixteen stations from 82—1265 m. (up to 2 %, once 16 %), at three stations showing displacement, and in Cores 184, 186—188, 192—194, 199, and 200, usually associated with displaced faunas. It is most abundant in Core 184.

Stomatorbina concentrica (Brady)

Pulvinulina concentrica Brady, 1864, Trans. Linn. Soc. Zool., vol. 24, p. 470, pl. 48, fig. 14.

Uchio (1952) places this species in the genus *Mississippina*, believing that the adult form differs from that of species of *Stomatorbina*. He says (p. 198) »— if adult form of *P. concentrica* is not included in *Stomatorbina*, then the genus *Stomatorbina* is valid, but if included, then the genus *Stomatorbina* Doreen 1948 is a synonym of the genus *Mississippina* Howe, 1930.» It seems very likely that the two genera are synonymous but the scarcity of species attributed to them is such that the generic variation cannot be properly understood. This species is reported in the North Atlantic mostly from 27—290 m. It is found at seven stations from 51—143 m. (up to 1 %) but does not occur in the cores.

Family ANOMALINIDAE

Cibicides aff. C. floridanus (Cushman)

(Plate 4, figures 36, 37, 38)

This species is common in the eastern Mediterranean and may have been specifically described, either as Recent or fossil, from this general area. This cannot be determined, however, from the figures and descriptions given and a study of the available types must be made to find out. The species is related here to Cushman's (*Truncatulina floridana* Cushman, 1918, p. 62, pl. 19, fig. 2) species which it resembles. The sutures are not raised as in *C. floridanus* s. s. but specimens from the Gulf of Mexico referred to *C.* aff. *C. floridanus* by Phleger and Parker (1951) and Parker (1954), which show a wide range of variation, include similar forms. Eastern Mediterranean specimens are more umbonate than those of *C. ungerianus* (d'Orbigny) from the Miocene of the Vienna Basin, and are larger, with thicker walls and less clearly defined chambers than those of *P. pseudoungerianus* (Cushman) from the Oligocene Byram marl. Similar ones apparently have been referred by various authors of Mediterranean faunas to these two species.

C. aff. *C. floridanus* is found at twenty stations from 106—2442 m. (up to 10 %), at four stations showing displacement, and in Cores 184, 186—189. 192—194, and 199, often in considerable numbers.

Cibicides kullenbergi Parker

(Plate 4, figures 34, 35, 40)

Cibicides kullenbergi Parker, 1953 *in* Phleger, Parker, and Peirson, Rep'ts. Swedish Deep-Sea Exped. (1947—48), vol. 7, no. 1, p. 49, pl. 11, figs. 7, 8.

Specimens are typical although their tests are usually somewhat smaller than those from the North Atlantic. Included in the population counts are specimens which are atypical in having a narrower keel and slightly more inflated chambers on the involute side. This is a true deep-sea form, reported in the North Atlantic deeper than 2100 m. It is not found in the surface sediment samples but occurs in Cores 186—189, 191—194, and 199, most commonly in Cores 186, 189 and 193.

Cibicides lobatulus (Walker and Jacob)

Nautilus lobatulus Walker and Jacob, 1798, Adams Essays, Kanmacher's ed., p. 642, pl. 14, fig. 36.

The specimens are very variable but show a continuous gradation from those having a low degree of convexity of the involute side to those having a high degree. The latter may be referrable to *C. refulgens* Montfort although none is as convex as his figured specimens. *C. lobatulus* has been widely reported in the North Atlantic. It is found at thirty-five stations from bay—1265 m. (up to 15 %), at six stations showing displacement, and in Cores 191—196 and 199 associated with displaced faunas.

Cibicides wuellerstorfi (Schwager)

(Plate 4, figures 41, 42)

Anomalina wuellerstorfi Schwager, 1866, Novara Exped., Geol. Theil, vol. 2, p. 258, pl. 7, figs. 105, 107.

This species is reported in the North Atlantic deeper than 630 m. It is found at one station at 1016 m. (3 %), and in Cores 184, 186, 193, 199, and 200, in a few scattered samples.

Hyalinea balthica (Schroeter)

(Plate 4, figure 39)

Nautilus balthicus Schroeter, 1783, Einleitung Conch. Kenntn., vol. 1, p. 20, pl. 1, fig. 2.

Hofker (1951) relates *Hyalinea* to *Streblus*, placing both in the Rotaliidae. The genus appears also to have affinities with the Discorbidae. *H. balthica* is reported to a depth of 2981 m. in the North Atlantic. It is found at eighteen stations from 106—799 m. (up to 6 %) most abundantly to 665 m., and in Cores 184, 186—188, 192—194, 199, and 200, usually associated with displaced faunas.

Planulina ariminensis d'Orbigny

(Plate 4, figure 43)

Planulina ariminensis d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 280, no. 1, pl. 14, figs. 1—3.

The specimens found in the eastern Mediterranean (max. diam. 0.83 mm., thickness 0.36 mm.) are somewhat thicker than those from Rimini (max. diam. 0.9 mm., thickness 0.22 mm.). The species is reported in the North Atlantic deeper than 275 m. It is found at twenty-five stations from 106—1016 m., mostly deeper than 200 m. (up to 5 %), at six stations showing displacement, and in scattered samples in Cores 184, 191, 192, 194, and 199, associated with displaced faunas.

Family PLANORBULINIDAE

Gypsina vesicularis (Parker and Jones)

Orbitolina vesicularis Parker and Jones, 1860, Ann. Mag. Nat. Hist., ser. 3, vol. 6, no. 5, p. 31.

This species is reported in the North Atlantic shallower than 143 m. It is found at six stations from 51—143 m. (up to 9 %), but was not observed in the cores.

Planorbulina mediterranensis d'Orbigny

(Plate 4, figure 44)

Planorbulina mediterranensis d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 280, no. 2, pl. 5 (14), figs. 4—6 bis.; Modèles, no. 79.

This species is reported in the North Atlantic mostly shallower than 150 m. It is found at fifteen stations from bay—567 m., mostly less than 256 m. (bay — 13 %; to 100 m. — up to 4 %; deeper — up to 1 %), at three stations showing displacement, and in Cores 188 and 191—193, associated with displaced faunas.

Planktonic Species

Family GLOBIGERINIDAE

Globigerina bulloides d'Orbigny

(Plate 5, figures 1, 2, 3, 4)

Globigerina bulloides d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 277, no. 1; Modèles, no. 76, no. 17 (juv.).

This species is variable, having 4—5 chambers in the final whorl. Small specimens (*Globigerina* sp., pl. 5, fig. 6) are included in the population counts of *G. bulloides* in some of the core samples and may represent a stunted form. One variant which is of particular interest (*vide* pl. 5, fig. 2: left-hand specimen and adjacent one on lower row) has a supplementary process over the aperture. This process is very similar to the »supplementary chambers» seen in *Globigerinita* and may have some connection with the reproductive cycle. Similar »chambers» have been observed in various planktonic species in the Mediterranean, but they usually occur very rarely.

Globigerina digitata Brady

(Plate 5, figure 8)

Globigerina digitata Brady, 1879, Quart. Journ. Micr. Sci., n. ser., vol. 19, p. 286; 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 599, pl. 80, figs. 6—10 (not pl. 82, figs. 6, 7).

Brady has included (at least) two species in his *G. digitata*. One form is trochoid throughout and should be referred to *Globigerina* (Brady, 1884, pl. 80, figs. 6—10). The other should be referred to *Globigerinella* (*op. cit.*, pl. 82, figs. 6, 7) being planispiral in the adult. The trochoid form is more widespread, occurring in both the Atlantic and Pacific oceans. The planispiral form is reported only from the Pacific and the writer has not observed it elsewhere. The more common, trochoid species is here designated as *Globigerina digi-*

tata. Since the writer is of the opinion that a lectotype should not be chosen without viewing the actual specimens, the specimens figured on pl. 80, figs. 6—10 are here designated as syntypes. It is possible that a study of these at first hand may reveal the presence of more than one species, one in the Pacific and one in the Atlantic. It is more probable that if there is a difference, which is doubtful, it is a subspecific one. The specimens figured on pl. 82, figs. 6, 7 must await study before a new species referred to *Globigerinella* can be erected. It would be preferable for this species to be defined from a complete suite of specimens from which a holotype can be chosen, Brady's specimens being put in the synonymy of this species.

The planispiral species mentioned above does not belong to the genus *Hastigerinella* Cushman, 1927, as stated by Galloway (1933), Bermudez (1952), and others. *Hastigerinella* as defined by Cushman (1927, p. 82) has club-shaped chambers having spines at the ends. The type species is »*Hastigerina digitata*» Rhumbler (1911, p. 202, pl. 37, figs. 9 a, b) (not *Globigerina digitata* Brady, 1879) which was renamed *Hastigerinella rhumbleri* by Galloway (1933). The observed specimens are generically distinct from either of the species figured by Brady and referred by him to *Globigerina digitata*. *Hastigerinella* is most closely related to *Hastigerina* which also has a very thin test wall, with spines on the peripheral areas of the chambers. The latter is planispiral while the former is not. The chief difficulty in putting *Hastigerinella* on a firm taxonomic basis is the difficulty of obtaining specimens. Due to the fragility of the test complete specimens are rare, if not completely lacking, in the bottom sediments. In the plankton itself specimens are exceedingly rare (J. S. Bradshaw, personal communication).

G. digitata occurs in both sediment and core samples in the Mediterranean. Even the juveniles can be easily identified as they show the typical flaring aperture though they have not the elongate chambers seen in the adults.

Globigerina eggeri Rhumbler

(Plate 5, figures 5, 7)

Globigerina eggeri Rhumbler, 1900, Nordische Plankton, pt. 14, Foraminiferen, p. 19, text figs. 20 a—c.

The Mediterranean specimens are smaller than those of the Atlantic and Pacific oceans, especially in the warmer portions, reaching a maximum diameter of 0.50 mm. In other respects they are typical. In the core sections that appear to reflect colder climates *G. eggeri* usually has a thicker test (pl. 5, fig. 5) than in the sections reflecting warmer periods (pl. 5, fig. 7). In some core samples the species has a very high frequency. These »floods» apparently bear no relation to climatic conditions, occurring in both »cold» and »warm» periods. Kullenberg (1952) related them to reduced salinity conditions caused by the »pluvial» or glacial times but if this were true they should occur only in the cold periods.

Globigerina inflata d'Orbigny

(Plate 6, figure 3)

Globigerina inflata d'Orbigny, 1839, in Barker-Webb and Berthelot, Hist. Nat. Iles Canaries, vol. 2, pt. 2, »Foraminifères», p. 134, pl. 2, figs. 7—9.

The Mediterranean specimens are variable, as are those from the vicinity of the Canary Islands, in the character of the wall which may be smooth or somewhat rugose and in the flatness of the dorsal side, which varies from flat to convex. These variations can be seen in the figured specimens. *Globorotalia oscitans* Todd may represent one of them. It has not been recognized here as a separate species.

Globigerina pachyderma (Ehrenberg)

(Plate 5, figure 9)

Aristerospira pachyderma Ehrenberg, 1861, Monats. k. preuss. Ak. Wiss. Berlin, p. 303; 1872 (1873), Abhandl. Ak. k. Wiss. Berlin, pl. 1, fig. 4.

This species is sometimes difficult to separate from the thick-shelled type of *G. eggeri* which is found in the core sections reflecting cold intervals. An attempt has been made to keep to a very rigid interpretation of *G. pachyderma*, including doubtful specimens in the population counts of *G. eggeri*, since the latter appears to be less diagnostic of temperature changes in this area. There is no doubt that the species are distinct but here, as in other cases, the line is sometimes difficult to draw.

Globigerina quinqueloba Natland

(Plate 6, figure 1)

Globigerina quinqueloba Natland, 1938, Bull. Scripps Instit. Ocean., Techn. Ser., vol. 4, no. 5, p. 149, pl. 6, figs. 7 a—c.

This species occurs in its typical form in the Mediterranean. Frequently associated with it are specimens (pl. 6, fig. 2) which appear to be similar except for the presence of a supplementary process over the aperture similar to that seen in *Globigerinita*. Since such a process has been observed on specimens of many species, there is some question of its generic or specific significance. Such specimens are included in the populations counts of *Globigerina quinqueloba*.

Globigerina radians Egger

(Plate 5, figure 10)

Globigerina radians Egger, 1895, Abhandl. k. bay. Akad. Wiss., München, Cl. II, vol. 18, pt. 2 (1893), p. 362, pl. 13, figs. 22—24. — Rhumbler, 1911, Ergebn. Plankton-Exped. Humboldt Stift., vol. 3 (1909), p. 148, pl. 29, figs. 2—4.

Rhumbler's reference is included in the synonymy because he more accurately figures this species, although Egger's figures are sufficiently similar to make the identification a plausible one. The test of *G. radians* is more compressed than that of *G. quinqueloba* and the chambers more elongate giving a more lobulate peripheral outline. There is frequently a long lobe-like extension from the last-formed chamber over the umbilical area. Similar specimens have been observed in material from the Pacific, The maximum diameter of the eastern Mediterranean specimens is *ca.* 0.34 mm. but most are somewhat smaller.

The species referred to »*Globigerina* sp.» in the northeastern Gulf of Mexico (Parker, 1954, p. 476) appears to be synonymous. I pointed out that this species resembled Rhumbler's (1911, pl. 30, figs. 1—6) »*G. lamellosa* Terquem» but it seems more probable that Rhumbler's species should be referred to *G. quinqueloba* since his specimens are less compressed and lobulate than *G. radians*.

Globigerinella aequilateralis (Brady)

(Plate 6, figures 5, 6)

Globigerina aequilateralis Brady, 1879, Quart. Journ. Micr. Sci., vol. 19, p. 71; 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 609, pl. 80, figs. 18—21.

The genus *Globigerinella* is closely related to *Globigerina* differing from the latter in becoming planispiral in the adult. Intermediate forms sometimes make generic identification difficult. *Globigerinella aequilateralis* in the Mediterranean, however, is usually planispiral in the adult form. The young forms are globigerine (*vide* pl. 6, fig. 5) but may be differentiated from similar specimens of *Globigerina bulloides* by the low, arched aperture. *Globigerinella aequilateralis* appears to be a reliable indicator of the warmer intervals reflected in the core sections.

Globigerinita glutinata (Egger)

Globigerina glutinata Egger, 1895, Abhandl. bay. Akad. Wiss., München, Cl. II, vol. 18, pt. 2 (1893), p. 371, pl. 13, figs. 19—21. — Rhumbler, 1911, Ergebn. Plankton-Exped. Humboldt. Stift., vol. 3 (1909), p. 148, pl. 29, figs. 14—26.

Mediterranean specimens are similar to those illustrated by Phleger *et al.* (1953, pl. 2, figs. 12—15). The supplementary process or »chamber» which covers the aperture is similar to that seen in many species as an occasional feature. In *G. glutinata* it is much more commonly present although by no means invariably so. It would be interesting to know what proportion of the specimens of related fossil species have this supplementary process. Here again, as in the case of *Globigerinella*, is a genus which is narrowly separated from *Globigerina*. As pointed out by Phleger *et al.* (*op. cit.*, p. 16), specimens are sometimes seen with a second aperture on the dorsal side. This in turn relates the genus to *Globigerinoides*. The planktonic genera are many of them so closely related that in a specific case it is often difficult to give a precise generic designation. For this reason some of the presently accepted genera might more appropriately be designated as subgenera.

Globigerinoides conglobata (Brady)

(Plate 6, figure 17)

Globigerina conglobata Brady, 1879, Quart. Journ. Micr. Sci., vol. 19, p. 72; 1884, Rep't. Voy CHALLENGER, Zool., vol. 9, p. 603, pl. 80, figs. 1—5; pl. 82, fig. 5.

Only typical adult specimens have been included in the population counts. Specimens which may be juvenile *G. conglobata* are included with »*G. rubra*, etc.» (pl. 6, fig. 16). The argument against this is that these small forms are almost always present whereas adult *G. conglobata* is comparatively rare. A further discussion of these small forms is given under *G. rubra*, etc.

One of the figured specimens (pl. 6, fig. 17, right-hand specimen) has a supplementary process over the aperture similar to that seen in *Globigerinita*. As previously mentioned this feature occurs occasionally in many species and it is suggested that it may have some connection with the reproductive process.

G. conglobata is rare in the surface sediment samples but occurs in the cores usually in sections reflecting warmer periods.

Globigerinoides rubra (d'Orbigny)

(Plate 6, figure 12)

Globigerina rubra d'Orbigny, 1839, *in* De la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foraminifères», p. 82, pl. 4, figs. 12—14.

At least three different species may be included in the population counts of »*G. rubra*, etc.» The first is typical *G. rubra* which has a smoother test than the following species and when present usually has at least some specimens showing a pink color. The second form (pl. 6, fig. 14) is referred by authors to several species which may or may not be synonymous. The best illustrated of these and the safest identification without seeing the types is *G. pyramidalis* (van den Broeck) (1876, p. 127, pl. 3, figs. 9, 10). Other possible designations are *G. elongata* (d'Orbigny) and *G. helicina* (d'Orbigny). The third species (pl. 6, fig. 16) is a very compact form which either represents juvenile *G. conglobata* or a species which cannot be easily differentiated from such juveniles. Possible identifications are *G. gomitula* (Seguenza) and *G. cyclostoma* (Galloway and Wissler). It is possible, however, that these two species may represent young forms of *G. rubra* or »*G. pyramidalis*».

Only *G. rubra* can be safely used for interpreting climatic conditions reflected in the cores as it is apparently found only in the warmest periods. Its presence is indicated in the distribution tables. All three species are found in the surface sediments. Occasional specimens possibly referrable to »*Globigerina* ? *helicina* d'Orbigny var. *aculeata*» Silvestri are found in the cores.

Globigerinoides sacculifera (Brady)

(Plate 6, figure 4)

Globigerina sacculifera Brady, 1877, Geol. Mag., vol. 4, p. 535; 1879, Quart. Journ. Micr. Sci., vol. 19, p. 73; 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 604, pl. 80, figs. 11—17; pl. 82, fig. 4.

This species includes specimens similar to those referred by various authors to *G. triloba* (Reuss) (*vide* pl. 6, fig. 4, lower specimens) but they appear to be within the normal variation of *G. sacculifera.* This species appears to be diagnostic of warmer periods in the cores.

Globigerinoides tenella Parker, n. sp.

(Plate 6, figures 7, 8, 9, 10, 11)

Test small for the genus, ratio of width to length *ca.* 6: 7; chambers rather rapidly increasing in size as added, four in the final whorl, rounded in outline; sutures depressed; wall roughened by dense, short spines; ventral aperture large, almost circular in outline, dorsal aperture small, narrow, at inner inner side of the final chamber, the earlier dorsal apertures in most cases apparently filled by shell material. Maximum diameter *ca.* 0.36 mm.

The holotype (U. S. N. M. P6129) and figured paratypes (U. S. N. M. P6130 a—d) are from ATLANTIS Sta. 4711, Lat. 34° 58′ N., Long. 19° 24′ E., at a depth of 3309 m.

Most specimens, including those at the type locality, are smaller in diameter than 0.36 mm. The test is shaped like that of *Globigerina bulloides* but differs in its smaller size, more sharply spinose test, and the presence of the dorsal aperture. *G. tenella* differs from *G. rubra* in its smaller size, less rounded outline, more spinose test, and smaller number of apertures. The specimens of this species were first thought to represent juvenile forms of some larger species of *Globigerinoides* but in tracing back the adult forms of known species to the juvenile stages they were isolated and found to be distinct.

Inadvertently in a few cases specimens of *Globigerina* sp. (pl. 5, fig. 6) were included in the population counts of *Globigerinoides tenella* in the cores. This is believed to have happened so occasionally as not to materially effect the population counts given in the tables. In general, the species is more common in the warmer periods of the cores. It is also found in the surface sediments.

Hastigerina pelagica (d'Orbigny)

(Plate 6, figure 15)

Nonionina pelagica d'Orbigny, 1839, Foram. Amér. Mérid., p. 27, pl. 3, figs. 13, 14.

This species occurs in its typical form. Occasional specimens are much more compressed and evolute than is typical, with an increased number of chambers. It is suggested that this represents a different stage in the life cycle of the species. The species occurs in the warmer periods in the cores, and in the surface sediments.

Orbulina universa d'Orbigny

(Plate 6, figure 13)

Orbulina universa d'Orbigny, 1839, *in* De la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foraminifères», p. 3, pl. 1, fig. 1.

This species occurs in its typical form. There are also many atypical forms, some of which are illustrated. Many bilobate specimens are found showing that great care must be taken in using such species as *»Orbulina bilobata»* d'Orbigny in stratigraphic work. It is believed that the complex of specimens containing bilobate, multilobate and single-chambered specimens may be referred to one species since the test walls are similar in all forms. It should be mentioned, however, that in many core samples only the single-chambered forms are seen.

Family GLOBOROTALIIDAE

Globorotalia punctulata (d'Orbigny)

Globigerina punctulata d'Orbigny, 1826, (nom. nud.), Ann. Sci. Nat., vol. 7, no. 8. — Fornasini, 1898, Pal. Ital., vol. 4, p. 210, text fig. 5.

Deshayes (1832, p. 170) describes a species, *Globigerina puncticulata*, in the synonymy of which he places d'Orbigny species (*G. punctulata*) of 1826, which in 1832 was a nomen nudum. Deshayes' species *G. puncticulata* is a valid one. This, in the writer's opinion, has no bearing on the legality of the name »*Globigerina punctulata*» d'Orbigny, 1898, which was established when Fornasini published d'Orbigny's figures from the »Planches inédites». The writer believes that Ellis and Messina in their »Catalogue of Foraminifera» erred in combining the two species. That they are not synonymous is obvious from Deshayes' description which is of a small globigerine form »composée de trois ou quatres globules bien séparés des un des autres» and having a maximum diameter of 0.2 mm.

Globorotalia punctulata is absent from the eastern Mediterranean surface sediments and occurs only once in Core 197 at a depth of 609.5 cm. It is suggested that the specimens at Rimini, the type locality, are probably derived from the nearby Tertiary outcrops. Phleger *et al.* (p. 20, pl. 4, figs. 8—12) give a list of synonymous species and figure specimens which are identical with the specimens found in Core 197.

Globorotalia scitula (Brady)

Pulvinulina scitula Brady, 1882, Proc. Roy. Soc. Edinburgh, vol. 11, p. 716.

Pulvinulina patagonica Brady, 1884, (not *Rotalina patagonica* d'Orbigny, 1839), Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 693, pl. 103, fig. 7.

This species occurs in the Mediterranean surface sediments and cores in its typical form. It is more common in the cores in the sections reflecting cooler periods.

Globorotalia truncatulinoides (d'Orbigny)

Rotalia truncatulinoides d'Orbigny, 1839, *in* Barker-Webb and Berthelot, Hist. Nat. Iles Canaries, vol. 2, pt. 2, »Foraminifères», p. 132, pl. 2, figs. 25—27.

This species occurs in its typical form in surface sediments and cores. It shows changes of coiling direction in the cores as shown in Figure 6. These changes are discussed in the section on the planktonic Foraminifera in the cores. Specimens are rare in the surface sediments but occur frequently in the cores, especially in the lower sections.

References

BATSCH, A. J. G. K.: Sechs kupfertafeln mit Conchylien des Seesandes, gezeichnet und gestochen von A. J. G. K. Batsch. — *4to*, Jena, 1791.

BERMUDEZ, J.: Resultados de la primera expedición en las Antillas del ketch Atlantis bajo los auspicios de las Universidades de Harvard y Habana. Nuevo género y especies nuevas de foraminíferos. — Mem. Soc. Cubana Hist. Nat., vol. 13, no. 1, pp. 9—12, 1939.

BERMUDEZ, P. J.: Estudio sistemático de los foraminíferos rotaliformes. — Bol. Geol. Min. Hidrocarbons, vol. 2, no. 4, pp. 7—230, 1952.

BRADY, H. B.: Report on the Foraminifera dredged by H. M. S. CHALLENGER during the years 1873—1876. — Rep't. Voy. CHALLENGER, Zool., vol. 9, pp. i—xxxi, 8—814, 1884.

BROECK, E. VANDEN: Etude sur les foraminifères de la Barbada (Antilles), etc. [recueillis par L. Agassiz, précédée de quelques considerations sur la classification et la nomenclature des foraminifères]. — Ann. Soc. Belg. Micr., vol. 2, pp. 55—152, 1876.

BROTZEN, F.: Foraminiferen aus dem Swedischen untersten Senon von Eriksdal in Schonen. — Sver. Geol. Unders., ser. c, no. 396, pp. 5—206, 1936.

COLOM, G.: Una contribución al conocimiento de los foraminíferos de la Bahía de Palma de Mallorca. — Instit. Español. Ocean. Not. Resúm., ser. 2, no. 108, pp. 1—53, 1942.

COLOM, G.: Estudio de los foraminíferos de muestras de fondo recogidos entre los Cabos Juby y Bojador. — Bol. Instit. Español. Ocean., no. 28, pp. 1—45, 1950.

Colom, G.: Foraminíferos de las costas de Galicia. — Bol. Instit. Español. Ocean., no. 51, pp. 3—59, 1952.

Cushman, J. A.: The Foraminifera of the Byram calcareous marl at Byram, Mississippi. — U. S. Geol. Surv. Prof. Paper 129-E, pp. 87—105, 1918.

Cushman, J. A.: Recent Foraminifera from British Columbia. — Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, pp. 38—44, 1925.

Cushman, J. A.: The Foraminifera of the Atlantic Ocean. Pt. 8. Rotaliidae, etc. — U. S. Nat. Mus. Bull. 104, pt. 8, pp. 1—179, 1931.

Cushman, J. A.: A monograph of the subfamily Virgulininae of the foraminiferal family Buliminidae. — Cushman Lab. Foram. Res., Spec. Publ. 9, pp. vii—xv, 1—228, 1937.

Cushman, J. A.: A monograph of the foraminiferal family Nonionidae. — U. S. Geol. Surv. Prof. Paper 191, pp. 1—100, 1939.

Cushman, J. A.: A study of the Foraminifera contained in cores from the Bartlett Deep. — Am. Journ. Sci., vol. 239, pp. 128—147, 1941.

Cushman, J. A.: Foraminifera, their classification and economic use. — Harvard Univ. Press, Cambridge, Mass., 4th ed., pp. 3—605, 1948.

Deshayes, G. P.: Historie naturelle des Vers, par Bruguières, 1879, continuées par Deshayes. — Encycl. méth., Paris, 1830—1832, 1832.

Emiliani, C.: Pleistoceme temperatures. — Journ. Geol., vol. 63, no. 6, pp. 538—578, 1955 a.

Emiliani, C.: Pleistocene temperature variations in the Mediterranean. — Quaternaria, vol. 2, pp. 87—98, 1955 b.

Ericson, D. B. and Wollin, G.: Correlation of six cores from the equatorial Atlantic and the Caribbean. — Deep-Sea Res., vol. 3, no. 2, pp. 104—125, 1956 a.

Ericson, D. B. and Wollin, G.: Micropaleontological and isotopic determinations of Pleistocene climates. — Micropaleontology, vol. 2, no. 3, pp. 257—270, 1956 b.

Ericson, D. B., Wollin, G. and Wollin, J.: Coiling direction of *Globorotalia truncatulinoides* in deepsea cores. — Deep-Sea Res., vol. 2, pp. 152—158, 1954.

Fichtel, L. von and Moll, J. P. C. von: Testacea microscopica alaique minuta ex generibus Argonauta et Nautilus ad naturam delineata et descripta. — *4to*, Wien, 124 pp., 1798.

Flint, J. M.: Recent Foraminifera [A descriptive catalogue of specimens dredged by the U. S. Fish Commission steamer Albatross]. — Ann. Rept. (1897), U. S. Nat. Mus., pp. 249—349, 1899.

Flint, R. F.: Glacial geology and the Pleistocene epoch. — John Wiley and Sons, New York, 589 pp., 1947.

Frizzell, D. L. and Keen, A. M.: On the nomenclature and generic position of *Nautilus beccari* Linné (Foraminifera, »Rotaliidae»). — Journ. Pal., vol. 23, no. 1, pp. 106—109, 1949.

Galloway, J. J.: A manual of Foraminifera. — Bloomington, Ind., pp. i—xii, 1—483, 1933.

Giunta, M.: Studio delle microfaune contenute in cinque saggi di fondo prelevati presso S. Margherita Ligure e Chiavari (Genova). — Arch. ocean. Limn., vol. 10, fasc. 1—2, pp. 67—108, 1955.

Guyot, M. A.: L'hydrologie du canal de Sicile. — Bull. d'Info., C. C. O. E. C., vol. 3, no. 7, pp. 269—280, 1951.

Herom-Allen, E., and Earland, A.: The Foraminifera of the west of Scotland. — Trans. Linn. Soc. London, Zool., ser. 2, vol. 11, pt. 13, pp. 197—299, 1916.

Hofker, J.: The Foraminifera of the Siboga Expedition. Part III. — Siboga-Exped., IV a, pp. 1—513, 1951.

Höglund, H.: Foraminifera in the Gullmar Fjord and the Skagerak. — Zool. Bidrag Uppsala, vol. 26, pp. 3—328, 1947.

Jones, T. R. and Parker, W. K.: On the Rhizopodal fauna of the Mediterranean, compared with that of the Italian and other Tertiary deposits. — Quart. Journ. Geol. Soc., vol. 16, pp. 292—307, 1860.

Kane, J.: Temperature correlations of planktonic Foraminifera from the North Atlantic Ocean. — Micropaleontologist, vol. 7, no. 3, pp. 25—50, 1953.

Kay, G. F.: Classification and duration of the Pleistocene Period. — Bull. Geol. Soc. America, vol. 42, pp. 425—466, 1931.

Koczy, F. F.: Echo soundings. — Repts. Swedish Deep-Sea Exped., vol. 4, fasc. 2, no. 3, pp. 99—158, 23 profiles (main, detail and photographic), 1956.

Kullenberg, B.: The piston core sampler. — Svenska hydr.-biol. komm. skr., Tredje ser.: Hydr. vol. 1, no. 2, pp. 3—46, 1947.

Kullenberg, B.: On the salinity of the water contained in marine sediments. — K. Vet. Vitt.-Samh. Handl., ser. B, vol. 6, no. 6, pp. 3—37, 1952.

Kullenberg, B.: Deep-sea coring. — Repts. Swedish Deep-Sea Exped., vol. 4, fasc. 1, no. 2, pp. 37—96, 1955.

Marks, P., Jr.: A revision of the smaller Foraminifera from the Miocene of the Vienna Basin. — Contr. Cushman Found. Foram. Res., Vol. 2, pt. 2, pp. 33—73, 1951.

Mellis, O.: Volcanic ash-horizons in deep-sea sediments. — Deep-Sea Res., vol. 2, pp. 89—92, 1954.

Murray, J.: On the distribution of the pelagic Foraminifera at the surface and on the floor of the ocean. — Nat. Sci., vol. 11, pp. 17—27, 1897.

Natland, M. L.: The temperature and depth-distribution of some Recent and fossil Foraminifera in the southern California region. — Bull. Scripps Instit. Ocean., Techn. ser., vol. 3, pp. 225—230, 1933.

D'Orbigny, A. D.: Tableau méthodique de la classe des cephalopodes. — Ann. Sci. Nat., vol. 7, pp. 245—314, 1826.

D'Orbigny, A. D.: Foraminifères. — *in* De la Sagra, Hist. Phys. Pol. Nat. Cuba, pp. i—xlviii, 1—224, 1839.

Oren, O. H.: Some hydrographic features observed off the coast of Israel. — Bull. Instit. Océan. Monaco., no. 1017, pp. 1—9, 1952.

Parker, F. L.: Foraminifera of the continental shelf from the Gulf of Maine to Maryland. — Bull. Mus. Comp. Zool., vol. 100, no. 2, pp. 213—241, 1948.

Parker, F. L.: Foraminifera species off Portsmouth, New Hampshire. — Bull. Mus. Comp. Zool., vol. 106, no. 9, pp. 391—423, 1952.

Parker, F. L.: Distribution of the Foraminifera in the northeastern Gulf of Mexico. — Bull. Mus. Comp. Zool., vol. 111, no. 10, pp. 453—588, 1954.

Parker, F. L.: Distribution of planktonic Foraminifera in some Mediterranean sediments. — Pap. Mar. Biol. and Oceanogr., Deep-Sea Res., suppl. to vol. 3, pp. 204—211, 1955.

Penck, A. and Brückner, E.: Die Alpen im Eiszeitalter. — Leipzig, 1189 pp., 1909.

Phleger, F. B.: Foraminifera of submarine cores from the continental slope, Pt. 2. — Bull. Geol. Soc. America, vol. 53, pp. 1073—1098, 1942.

Phleger, F. B.: Ecology of Foraminifera, northwest Gulf of Mexico. Pt. 1, Foraminifera distribution. — Geol. Soc. America, mem. 46, pp. 1—88, 1951.

Phleger, F. B. and Parker, F. L.: Ecology of Foraminifera, northwest Gulf of Mexico. Pt. 2, Foraminifera species. — Geol. Soc. America, mem. 46, pp. iii—iv, 1—64, 1951.

Phleger, F. B, Parker, F. L., and Peirson, J. F.: North Atlantic Foraminifera. — Repts. Swedish Deep-Sea Exped., vol. 7, no. 1, pp. 3—122, 1953.

Pollak, M. J.: The sources of the deep water of the eastern Mediterranean Sea. — Journ. Mar. Res., vol. 10, no. 1, pp. 128—152, 1951.

Reuss, A. E.: Neue Foraminiferen aus den Schichten des österreichischen Tertiärbeckens. — Denkschr. Akad. Wiss. Wien, vol. 1, pp. 365—390, 1850.

Rhumbler, L.: Nordische plankton — Foraminiferen. — Nord. Plank., vol. 14, 32 pp., 1900.

Rhumbler, L.: Die Foraminiferen (Thalamophoren) der Plankton-Expedition, etc. Pt. 1. Systematik. — Ergeb. Plankton-Exped. Humboldt Stift., vol. 3, pp. 1—331, 1911.

Rouch, J.: Observations océanographiques de surface dans l'Océan Atlantique et dans la Mediterranée. — Ann. Instit. Océan. Monaco, vol. 20, no. 2, pp. 51—73, 1940.

Rouch, J.: Température et salinité de la mer à Beyrouth. — Bull. Instit. Océan. Monaco, no. 884, pp. 1—6, 1945.

Rubin, M. and Suess, H. E.: U. S. Geological Survey radiocarbon dates II. — Science, vol. 121, no. 3145, pp. 481—488, 1955.

Ruscelli, M.: Foraminiferi de due saggi di fondo del Mar Ligure. — Atti Accad. Ligure Sci. Lett., vol. 6, fasc. 1, pp. 1—31, 1949.

Schott, W.: Die Foraminiferen in dem äquatorialen Teil des Atlantischen Ozeans. — Wiss. Ergeb. Deutsch. Atl. Exped. Forsch. Vermess. »Meteor« 1925—1927, vol. 3, pt. 3, sect. B, pp. 43—134, 1935.

Seguenza, G.: Prime ricerche intorno ou rhizopodi fossili delle Argille Pleistoceniche dei dintorni de Catania. — Atti Accad. Gioenia Sci. Nat., ser. 2, vol. 18, pp. 85—126, 1862.

Seguenza, G.: Le formazioni Terziarie nella Provinciadi Reggio (Calabria). — Atti Accad. Lincei, ser. 3, vol. 6, pp. 1—446, 1880.

Sidebottom, H.: Report on the Recent Foraminifera from the coast of the Island of Delos (Grecian Archipelago). — Mem. Proc. Manchester Lit. Philos. Soc., 1904—1909.

Smout, A. H.: Lower Tertiary Foraminifera of the Qatar Peninsula. — Brit. Mus. (Nat. Hist.). pp. 1—96. 1954.

Suess, H. E.: Absolute chronology of the Last Glaciation. — Science, vol. 123, no. 3192, pp. 355—357, 1956.

Sverdrup, H. U., Johnson, M. W., and Fleming, R. H.: The oceans. Their physics, chemistry and general biology. — Prentice-Hall, Inc., N. Y., pp. v—x, 1—1087, 1942.

Uchio, T.: An interesting relation between *Stomatorbina* Dorreen, 1948, and *Mississippina* Howe, 1930, of Foraminifera. — Trans. Proc. Paleont. Soc. Japan, n. s., no. 7, pp. 195—200, 1952.

Wiseman, J. D. H. and Ovey, C. D.: Recent investigations on the deep-sea floor. — Proc. Geol. Assoc., vol. 61, pt. 1, pp. 28—84, 1950.

Zeuner, F. E.: Dating the past — an introduction to geochronology. — Methuen and Co., London, 3rd. ed., pp. v—viii, 1—495, 1952.

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TABLES

	AEGEAN																		E. MED	
STATION	4662A	4666	4661	4658	4667	4657A	4649A	4654A	4668	4654B	4652	BS21	BS20	4657B	BS29	4648	4647	4657	4681	4711
DEPTH IN METERS	51	71	75	82	86	104	106	115	117	143	201	205	210	256	287	338	366	384	2852	3309
Globigerina bulloides	25	13		10	21	35	4	18	11	19	30	34	35	33	20	22	19	29	14	17
digitata		8		1				1					2						3	2
eggeri				2	4	4		4		10	21	13	6	15	12	10	7	9	6	8
inflata	13		1		4	3	.6		2	1	2		2			1	2	.4	.2	4
pachyderma																1	3	.4	.5	2
quinqueloba		4	1	2		3	.6			2	3	3	1	.4	.5	8	3	1	.2	2
radians															.5					1
Globigerinella aequilateralis						2		3		2	3	3	4	2	1	2	2	3	4	5
Globigerinita glutinata					4	2		1		2	1	1	2	.4	1	1	.4	2	.7	6
Globigerinoides conglobata																				.1
rubra, etc.	62	71	93	81	51	44	91	67	72	54	35	43	44	46	61	53	56	50	56	37
sacculifera			1		8	1	1	2	11	4	2		2	1	1	1	6	1	7	4
tenella		4	3	4	8	5	2	3	2	3	.4	3	1	.4	2		.4	3	4	3
Globorotalia scitula																				4
truncatulinoides																	4			1
Hastigerina pelagica										1									.5	
Orbulina universa			1			1	.6	.4	2	2	2		1	1	1	1	.4	.4	4	4
% of total fauna	3	6	12	14	7	21	30	51	18	25	32	20	20	41	36	25	76	57	99+	99+

TABLE 2. Distribution of planktonic species in selected surface sediment samples in per cent of total planktonic population.

STATION	BS32	4662A	4666	4661	4658	4667	4657A	4649A	4654A	4668	4654B	4721A	4652	BS21A	BS20	4657B	BS29	4648	4647	4657	4718	4694	4723	4687	4685	4664	4660	4714	4656	4713	BS9	4654	4686	4702	4650	4670	4671	4693	4649	4688	4716	4705	4673	4678	4683	4689	4698	4701	4681	4710	4711	4708	4676	BS1	4733	4659	4675	4655	4691	4665
DEPTH IN METERS	Bay	51	71	75	82	86	104	106	115	117	143	179	221	235	210	256	287	338	366	384	541	567	567	631	647	658	665	665	680	684	731	746	799	799	859	996	1016	1073	1265	1312	1378	1788	1844	1862	2358	2442	2738	2760	2852	3241	3309	3499	3974	462	552	850	1064	1102	1331	1587
Angulogerina angulosa												2	.6					.4	.7		1		4								.4																							.5			5			.7
Articulina tubulosa & vars																														.5			.5						.6											13	20						1		1	
Asterigerinata mamilla	4	13	4	38	5	2	3	.5	16	11	9	4																																										5				1		.5
Astrononion stelligerum		2	.3	1	1		.3		.5	.4	.6														.3												.3																	.3						
Bigenerina nodosaria			.6	.6	2	2	.2	6				.5	1	1	2	5	3	.7	2	.3	4		2		1	.2					3		.5																					.5						
Biloculinella labiata								.3									.3	.4		.5		3	.8	3	1		.3	.6	.5	3	3	1	.5	1	.3	2					5														2	.3		2	1	
Bolivina albatrossi																						.4	.4							1							4				2															.3	4		7	.5
attica					.2	1	.5	.7			.6				2			.4				1																																						.5
catanensis			5		4	8	3	8			.3		2	2	8	4	2	2		5		2													1		.3																			1		.3		7
difformis									.5		3		.3										.8																															1					2	
dilitata dilitatissima								2					1	2	3	1	1	3	3	2			.4			9	9		.5			6			3		2				2															6	1		18	9
pseudoplicata							.3				.3	5											.4			.2				5					.6													50						2				.3	4	.2
subaenariensis								.3			.3																																																.6	
Bulimina aculeata																																																												
costata					.6	.6		1			.6		1	3	4	9	10	15	4	10	5	11	2	2	7	14	16	.4	1	.8	.4		.5	.5	5	1			2								6			3				1	.4	20	3	2	5	5
exilis																																																												.2
gibba			1		4	2	4	.1				4	3	1	3	9	5	1	6	.6						1																												.3						
marginata					.2	.6		6			.3	.5	2	6	5	3	7	5	7	3	6	6	.4	12	13	2	1	4	1	2	.4		6			4	.6																	.5	5	.6	1	1	1	4
Cassidulina carinata			12		7	7	8	5		1		4	5	3	2		4		3	2	1	1	2			1	.5	.2		.2						.6																		.3		1	1	3	4	7
crassa							3		.5	2	3		3	.3	.1			.4	.7	2		5	2	2	1	.5		4	1	7		4	1		2	5	.6		1		2													2	.1		2	3	.7	1
cf oblonga		.1	4	.4	4	1	9	1	3	2	3	4	5	1	2	2		.4	1	.5							.5							.5		.6																		.3				1	.3	2
subglobosa																		.4			1		2	1				2		1	2		.5				.3																		5				.6	
Chilostomella mediterranensis																						.2			.3	.7		.2													2																.4		.7	1
Cibicides aff. floridanus												.5		3	.4		4	3				7	.8	3	10	6	7						2		.3		4		2							8										2	1		5	1
lobatulus	5		3	1	6	4	6	7	14	3	5	5	7			3	2	2	3		1	.4	2			1	.3	.2	2		1	.7	2			3	.6	4	2															13	.5	.8	3	3		6
wuellerstorfi																																					3																							
Eggerella bradyi, etc																																																									.4			
Elphidium advena	.4	2	.3			.6	.5	.3		2		5																																										1						.5
complanatum	2	.6	.3	.2	1	.6			3	7		.5	.6	.3																																									.2					2
crispum	6	7		4	2	3	2	2		.4		5	6		.2			.4								.2																												7						.5
granosum		4	6		6	3	3					.5	.3																																															
cf minimum	.4	4	4	.4	2	.5		.7				.5																																												.3		.3		.2
pulvereum								.5				.5	.6																																									1		.6				1
verriculatum		2			3		.5	.7			.3		.6																																														.3	
spp																	.3																																							.3				
Epistominella rugosa convexa																					2	.2	2					8		13	3		2	3			.6													3					1		.4			
Eponides repandus		.2		2			5		2	4	4		1							.3		.2																																						
Gavelinopsis praegeri			.3		.3	2	3			2	5		2	.3	1		.3	1	.7	.6		.7	2			.2		.2			.4	.7	.5	.5	.6				.6															1		.3	1	2		2
Globobulimina pseudospinescens																										2	2																													3			.6	.5
Glomospira charoides									1				.3					.4	.7	2		2		2	2			3	2	.6	8	6	5	3	3	4	1	20	10	13	5		10	54	90	25	82	38	100	66		67		.3	1		.4	5		
cf gordialis																						2		.6	.3			7	2	3		.7	1	4		10	1						2			8				3					4		3	.3		
Gypsina vesicularis		.6		2				.3	9	4	6																																																	
Gyroidina altiformis														2	.7	.6	2	1	8	3	4	.7	2	2	3	9	7	2	15	3	5	32	4	3	26	5	5	4	34	11	12	18	14	23	5	8								.3	5	21	4	13	.4	2
cf. neosoldanii								.3					.3	.7	2	2		3	3	5	2	4	.4	6	2	3	1	4	5	6	11	4	5	21	3	20	9	36	15	67	49	82	64	19	5	18	6								2	.6	6	.6	.4	
umbonata								.3							.2	2	1			.6		.7		.3	.3	.2					1	.7			1	.6	.3																		.2	.6		1		.5
Hanzawaia rhodiensis		.6		2		5	5	4				5				.3	.3	.7	2	.3		.2	3					1			.4			1			1				2													1	.4	.3	3	2		2
Höglundina elegans					.2			.3				.5	1	.7	2	3		4	2				2					.2		.2		.7					16		.6																5		.4		1	
Hyalinea balthica								2				2	3		3	6	2	6	2			7	.4	1	3	1	2	.6			.4		.5																					.3		.3		.6	1	.7
Involutina cf planorbis											.3		.3							.6			.4	.3	.6			2		2	1	6	2	1	1		1	7	2	2						8									.2			.3		
Lagenonodosaria scalaris					.3	.3			.5		.3	3	2	1	1	4	2	.4	5	2	2	.7	2	.6	2			.2		.6	1			.5		.6																		.5			.4	.6		1
Lenticulina peregrina																						1						1	5	2	4					2	.3																	.3	4					.2
Loxostomum alatum														.7	4			.4				.2	.4			.5				.2																										.3				1
Miliolidae	4	2	2	9	7	8	.0	4	4	1	3	.4	3	3	2	2	2	3	1	4		5	6	3	1	3	.6	2	3	5	3	4	4	2	3	3	4	4	4		2							12			20			23	2	3	3	4	4	5
Miliolinella circularis	2	.6	3		6	3	7			.4	2	5	3		2	6	2	.4	.7	2		2	8	6	1				2	1	1		2		2		3		4		2										5			1	4	.3	4	2	2	4
Neoconorbina terquemi				3	4	5				3	.7		.6	.3			.3	1				.2	.8			.7			.5					2																				5	1	.3	2	1		1
williamsoni										.4		5																																												.3	.4			.5
Nonion barleeanum, etc		4	8		6	5	5	3		3		5	1	2	2	7	8	7	3	5	1	.7	5		2	.3	12	24	10	7	4	10	1	42	32	8	5		14				6										13	.5	9	16	11	19	10	6
sp. B							.3						.3										.8																																	.3		.3		.2
Nonionella turgida						.3									2							.4																																						.5
Patellina corrugata																							.4														.3				2													.5	.5					.2
Peneroplidae	6																																																											
Planorbulina mediterrerranensis	13		2	.2	2	4		.7		.4	.6		.3	3	.7	.6							.4																															2		.3				2
Planulina ariminensis								.3					2		4	2	.5	3	1	5	4	3	1	5	4	2	3	5	.5	4	1		3	1	1	.6	4																	.5	5	1	3		.4	.7
Pseudoclavulina crustata								.5				5	2	.3	.7		2	1			1	3	.8	2	1	2	1	.2			1																													
Pullenia quinqueloba					.2				.5		.3			.3			2	.4		.6			2				.3		1		3					.6			.6																	.6		.6	.3	
Pyrgo anomala											3	.5	.6	.7	.2	3	.5			.6	2	.2							1	.2																													.4	.7
murrhina																																																			5									
Pyrgoella sphaera					.2																																																		.2			.6	.6	
Quinqueloculina aff lamarckiana					5		1		.5		3		.6	3	.2	2	2	1	1	2				.3		.7	.3		.5								1																			.3	1		.3	
Reussella spinosissima	.8	3	4		2	4	2	1		2																																									5							6		
Robertina translucens												5			2	.3	.3					2	.4	.6				.6		1	1		.5				.3		.6											3					.2		.4	.3	.6	.5
Robulus spp		.2		1	.2		1	3	1	1	3	1		.7		3	.3	4	3	1	4	1	.8	2	.3	.5		2	.5	8	1					1	2																	1	2	.6	4		.4	
Rosalina aff columbiensis		4		4				1				1	.3					4																																		33		2	.4	.8	1	2	.7	3
globularis bradyi			3	.2			.3				.6																																											4			2			
obtusa	7			2	.2				9	4	2	5		7	4	3	.3												.5					.5		.6																		4		.6		2		1
suezensis				6	2	2					.3			.7	2	.3						.2																																				3		.5
spp		4						3																																														3						
Rotalia granulatus	.6	2	4			1		3			.3																																																	
Rotamorphina ? involuta																						4		.3				5		1		.7		.5	.3	1																			.2	.3		1		
Sigmoilina distorta		.2			2	.6		7				.5	.3	.5			1	1		2	1	4	2	.6		2	1	.4	1	2	.4																				45				.4					.5
schlumbergeri												2	.6	7	.2				3	.3		7	2	6	3	4	2									.6	.6																			.8		.6		
tenuis														.3				.4		3		7		6	6						1		.5		.6		.3																		2	1		.3	3	.5
Siphonina reticulata							1	.7	5			1			2			1	4	7	3		.4	.3	.3	.2		2	1	3				2		.6	1																	.3	3			1		
Siphotextularia concava		.2			2	.6		3			2	.5	.6	3	4	.3					2			3																																	.4	.6		.7
Sphaeroidina bulloides				.2			.3	2				5	2	4	2	3	3			2		4	.8	1	1	4	3	.6		.3	4				1	2	1	2	.6																.4	.8	1	.3	2	.7
Spirillina vivipara			.3	1	.2	.3				2	3			.3														.2		1	.4			2		.6																		1	.2	.6		.6	.4	.5
wrighti				.2					3	3	3																																											.5	.2					
Spiroloculina angulosa						.3		.5		.4			3	.7	4		1				1																.6																	.5	.2	.3				
canaliculata			.3	.6		.6	5	.3		.4	.3			.7		.3	5					.7	.4	1	1	.2			1								.3																	3	.2					.2
grata	.8			2	.3	3	.5		.5			5			.2		5						4							.2					.3																			.3	2	.8		1	3	.5
Spirophthalmidium acutimargo														.5			2	1	.7			2		2	.3			1	.5	3	14		3	.5			1				5													.3			1		1	.2
Stomatorbina concentrica		2		2	2		1			.4	3																																																	
Streblus beccarii & vars	2	7	4		2	5	.5					2																																												.3		.6		1
Textularia calva	2	3	4	3	3	2	2	5	3	2	5	2	5	2	2	2	2	2	2	.3			1																																					
conica		.4	1	2	.3	.3		3	2	.4	3		2				.5	1	2	.3	1	.2	1	1																																	.4			
sagittula		1	.3	7	4	2	5	2	2	9	6		5	2	2	3	2	.4	2												.4																							.5						1
Uvigerina auberiana												1	2				1	3	3	5	9		3	.6	.6			3	.5	7	1								.6															.3	4		.4			2
mediterranea					.6	.3	3	10	5			5	11	21	22	19	9	16	13	26	35	8	22	37	33	.4	28	5	41	3	16	7	48	3	7	13	19	7	3		2					25	6			6					22	9	.4	10	4	1
peregrina																																					4																				2		5	
Valvulineria complanata		.2	2		.3	1	3			.4				2	2	.3	.3								.3	.2							.5																											
Virgulina complanata																																																					13							
mexicana																																																					61							.2
Miscellaneous spp	5	4	3	3	3	6	5	1	6	12	7	5	2	2	3	1	6	4	5	1	7	15	8	4	4	3	1	8	4	10	6	6	4	6	4	8	2	16	3	7	6		4	4						3			3	11	1	2	15	9	7	7
% of total fauna	100	97	94	88	86	93	79	70	49	82	15	38	68	80	80	59	64	75	29	43	2	40	16	46	36	85	79	6	8	13	3	12	.	6	44	3	5	2	12	1	<1	<1	1	<1	<1	<1	<1	<1	<1	1	<1	<1	1	65	6	68	6	14	41	73

TABLE 3. Distribution of benthonic Foraminifera in surface sediment samples in per cent of total benthonic population.
Stations with large displaced faunas are in section at right.

CORE 184

SAMPLE	1	2	7	19	21	22	23	25	29	34	35	37	41	46	48	49	54	58
DISTANCE FROM TOP (CM)	0.5-1	9.5-10	59.5-60	179.5-180	199.5-200	209.5-210	219.5-220	239.5-240	279.5-280	329.5-330	339.5-340	359.5-360	399.5-400	449.5-450	469.5-470	479.5-480	529.5-530	569.5-570
PLANKTONIC POPULATION (%)	390	1200	100	70	70	100	200	70	70	560	430	400	230	310	1400	1000	1500	620
Globigerina bulloides	1	1	1	6	1	1		6	3	3	6	3	1	4	4	3	4	3
digitata	3	.6	1				.5		1									
eggeri	15	10	7	12	7	1	.5		12	5	16	12	10	12	10	8	26	24
inflata					3		5			2	2	1	2	.3	1			
pachyderma										1	6	10	9	8	7	14	7	3
quinqueloba							.5			.5	3	4	2	9		2	7	16
radians	.3									.7	.7	1		.3				
Globigerinella aequilateralis	4	6	6	1	4	5	4											
Globigerinita glutinata		.3	3		14	11	6	14	12	3	3	2	2	2	2	4	1	1
Globigerinoides conglobata											.5							
rubra, etc.	71	65	77	57	43	75	50	78	69	84	56	58	61	57	70	61	44	49
(typical G. rubra present)	x	x	x	x	x	x	x	x	x				x	x				x
sacculifera	2	8		23	27	6	27	1										
tenella	1	5	1					1										
Globorotalia scitula										.5	3	5	7	2	3	8	10	4
truncatulinoides							5		3		3	4	6	4	3			
Hastigerina pelagica		.3					.5											
Orbulina universa	2	3	4	1	1	1	.5								1			
BENTHONIC POPULATION (actual numbers)	12	8	0	13	55	199	135	30	111	106	189	214	113	189	207	268	229	242
Articulina tubulosa & vars.									2		4	1	1	1	4	5	4	
Bolivina albatrossi									5	7	14	9	3	7	32	27	20	11
dilitata dilitatissima						13	79	11	45	13	48	50	31		18	39	58	58
pseudoplicata											1	2		2	1	9	3	1
subaenariensis							7			3	11	20	1	42	1	3		1
Bulimina costata									26	12	16	12	8	12	5	8	6	8
gibba											1	2		3				2
marginata										8	14	11	10	13	8	15	8	17
Cassidulina carinata										6	9	13	6	31	2	11	16	8
crassa															3	6	3	1
cf. oblonga										2	1	5	3	1	3	1	2	3
Chilostomella mediterranensis				13	17	66	22	7	1	2	2	1		4				
Cibicides aff. floridanus										9	8	6	6	11	18	20	30	22
wuellerstorfi										3	1			1			2	4
Elphidium spp.															2			
Gavelinopsis praegeri, etc.														1	1	1	1	
Globobulimina affinis						100		8	20	2	12	21	13	11	4			
pseudospinescens					35		21	1			1							
Glomospira charoides	1	2																
Gyroidina altiformis	3								1	10	3	3	3	1	8	3		
cf. neosoldanii	1	2							1	3				1	4	2	1	1
umbonata													1			1	1	4
Hoglundina elegans									4		6	2	1	3	32	12	7	
Hyalinea balthica										2	3	12	5	6	1	11	1	14
Involutina cf. planorbis	2	1																
Loxostomum alatum							5	2	1	2	2	7		6	1		1	1
Miliolidae									1	1	5	3	1		6	10	9	1
Miliolinella circularis		1							1	2	1	2		1		11	2	
Nonion barleeanum, etc											3	3	2	7	1	5		1
Planulina ariminensis											2			2	3	10	2	9
Pullenia quinqueloba										1		1						2
Pyrgo anomala										2		1	1		1	1	1	
murrhina										1		2	1					
Pyrgoella sphaera													1				2	
Quinqueloculina aff. lamarckiana										1			1		1	3		
Robulus spp.												2	1		1			
Sigmoilina tenuis										2	1		2			1		
Sphaeroidina bulloides										1	3	1		2	1	1	6	2
Spirillina vivipara																2		
Uvigerina mediterranea	4									11	6	11	5	4	25	18	6	20
peregrina											6	5	2	8	9	15	33	48
Virgulina mexicana		2			3	16	1	1						3				
Miscellaneous spp.	1					4			2		1	5	4	5	11	13	3	3
spp listed elsewhere									1		3	1				4	1	

TABLE 6. Distribution of Foraminifera in selected samples from Core 184.

	CORE 186																																								
SAMPLE	1	2	4	5	6	7	9	13	18	24	28	32	37	42	46	49	50	51	53	54	59	60	61	65	67	70	72	73	74	75	77	80	81	82	83	85	86	88	90	94	98	106
DISTANCE FROM TOP (CM.)	0.5-1	9.5-10	29.5-30	39.5-40	49.5-50	59.5-60	79.5-80	119.5-120	169.5-170	229.5-230	269.5-270	311-311.5	359.5-360	409.5-410	449.5-450	479.5-480	489.5-490	499.5-500	519.5-520	529.5-530	579.5-580	589.5-590	599.5-600	639.5-640	659.5-660	689.5-690	709.5-710	719.5-720	729.5-730	739.5-740	759.5-760	789.5-790	799.5-800	809.5-810	819.5-820	839.5-840	849.5-850	869.5-870	889.5-890	929.5-930	972-972.5	1050-1050.5
PLANKTONIC POPULATION (%)	1600	580	40	4[illegible]0	830	180	730	1100	3200	1800	2100	3700	2700	1500	650	6700	2600	3200	840	2000	2400	3900	2200	2600	4000	7400	2900	2600	6500	2500	980	380	4400	3300	2800	8900	2500	4700	110	1800	6500	5700
Globigerina bulloides	4	7	9	7	16	18	10	13	8	22	17	19	15	20	10	17	19	15	16	17	15	16	17	15	20	14	17	12	18	10	16	11	21	12	16	14	15	15	5	24	6	16
digitata	1																				.3	.6																				
eggeri	.5				16	5	19	14	10	26	17	22	18	15	9	42	5	14	14	21	8	22	26	34	26	50	20	18	33	23	28	6	43	51	49	53	60	61	51	52	70	57
inflata				.4	7	.6	5	6	1	5	4	9	11	11	20	2	2	6	10	4	8	2	5	4	7	2	9	8	6	7	5	15	3	3	3	2			2			
pachyderma					2		2	2	11	8	4	2	1	3	1	9	2	.5	2	7	1	4	3	2	4	4	1	1	2	2	4	1	11	2	6	3	1	1	1	2	2	1
quinqueloba					7	3	2	2	1	7	5	6	4	5	3	7	5	1	3	6	4	9	10	3	1	9	3	3	3	2	8	2	3	12	6	13	17	21	35	13	16	17
radians						.6																	.4		1		.3															
Globigerinella aequilateralis	5	2		2									.6	.3	.3			.7		.6	.3	.6		2	2		.5						.4			.4						
Globigerinita glutinata	1			10	4	8	4	2	6	1	3	1	2	2	1	2			1	3		2	4	4	2	2	.5	2	2	5	3		2	4	4	2	7	.3	1	2	2	9
Globigerinoides conglobata														.3				1							.4	.4					.4				.6							
rubra, etc.	78	90	73	66	44	60	50	50	55	19	38	33	43	35	41	10	66	54	40	28	57	34	24	26	22	10	33	27	22	28	19	39	10	10	11	4		1	4	4		
(typical G. rubra present)	x	x	x	x		x		x		x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x			
sacculifera	8		18	13			1	1		1	.4			.3				.5		.6		2	1	1	1	.6	.3	.3	2	10	4	11	2		.6	.4				.6		
tenella					2	3	3	.6		1	2	1	1	1	5	1		1	3	3	1	2	2	.6	1	1	.3	5	2	1	2	.5	.5	.5	.3	.4						
Globorotalia scitula					2	.6	1	2	7	7	8	5	2	2	2	8	1	2	3	4	4	3	5	3	10	5	4	1	4	3	4	.3	2	1	1	6				.4		
truncatulinoides				1		.6	1	5					.3	.5	.3				6	.4	.3			1	.4	.4	3	20	4	1	1	10		1								
Hastigerina pelagica		.3																									.3															
Orbulina universa	2	.7		.6		.6	2	2	.6	3	3	2	2	4	7	2		4	2	5	.7	2	2	4	2	1	7	2	2	8	5	3	2	3	2	1		.7	1	2	4	
BENTHONIC POPULATION (actual numbers)	4	1	9	1	9	11	62	29	26	20	62	83	67	32	47	45	53	33	15	21	35	25	30	17	10	63	16	28	93	16	4	11	19	5	9	105	1	0	0	6	0	0
Articulina tubulosa & vars.							2	2		1	4	3	7	1	14	6	31	1	1	1			1			5			1	1		2	3	1		12						
Bolivina albatrossi						1		4			1	2	3	2		2	1	3		3	1	3	5			4	2	8	2	2		3			1	4						
catanensis				1									1				2	1				1							10	1				1								
dilitata dilitatissima			1			1					1			1	1								1						22	1					4							
Bulimina costata									2	1	7	4	4	1	2	4	5					1		4		4			1	1			1			4						
exilis								1		2	2	2	3	2		4			1		1	1	2		2	31			3	2	1					46	1					
marginata														1															3	1			1		1							
Cassidulina carinata					2	5			5	3	2	7	7	3	11	1	4	3		1	2		1			1			12				1			2						
crassa																	1		2																							
cf. sicula																																				2						
Cassidulinoides tenuis																																				3						
Chilostomella mediterranensis			5						1											1								1	1							1						
Cibicides aff. floridanus		1	1		2		38	4	16	2	21	23	15	5	10	1		1																		2						
kullenbergi												1	3			3				2	1	2	1			2	4	1	5	1			3		1	2				1		
wuellerstorfi									1		1	2	2	1			1																									
Eggerella bradyi, etc							1	1			1	1										3		2	1	2		2	9	3			1			3				1		
Epistominella rugosa convexa												1		1				3	1					1									1									
Gavelinopsis praegeri, etc.								2				1		1		1							1																			
Globobulimina affinis	1				1	1	2	2		1	3	3	5	4		3			1	5				3	1		5	9	5	1		5	3	1	1	1						
Gyroidina altiformis											1	1						3		1		1																				
delicata																																				2				3		
cf. neosoldanii	2				1			3			1	3	2					1	4		6	2	3	2		4	1	3		1	3		1			3						
Hanzawaia rhodiensis																													2													
Höglundina elegans								1		2		3	2		1	1					5	5	7	1				1	1													
Hyalinea balthica																1			1	2																						
Miliolidae					1	1	9	2	1	2		5	2	2	2	4		2		1		1	1	1	2	1		2		1			1			3						
Miliolinella circularis							4	1				7	4	5	2	3	5	8	1	1	14			1		1	1		2							1						
Pseudoeponides umbonatus var																1													1							1				1		
Pullenia quinqueloba											1	1	1		2	1				1																						
Pyrgo anomala							2	1				1				2					1				2																	
lucernula							2	2			3					1		3								1	3		2													
murrhina										2	3	1														1																
Quinqueloculina aff lamarckiana												3																	1													
Robertina translucens																2		1			1	1			1				2							1						
Robulus spp.												1										1				1																
Spiroloculina canaliculata													1				1	1				1																				
Uvigerina peregrina					1					2	5	2	2	1	1		2		1										2													
Virgulina mexicana			1																							1										1						
Miscellaneous spp.						2	2	1		1	5	4	3	1	1	3		2	2	2	3	1	7	2	1	4			3				3	2	1	11						
spp listed elsewhere	1		1		1			2		1		1				1						1						1	3			1										

TABLE 7. Distribution of Foraminifera in selected samples from Core 186.

CORE 187

SAMPLE	1	2	7	10	16	18	19	21	22	23	24	29	31	33	34	35	37	38	42	46	47	48	50	51	52	53	55	57	62	65	69	70	72	73	74	75	77	79	82	83	84	85	86	88	94	95	96	97	99	100	101	102	103
DISTANCE FROM TOP (CM)	3-35	9.5-10	59.5-60	87.5-88	149.5-150	169.5-170	179.5-180	199.5-200	209.5-210	219.5-220	229.5-230	279.5-280	299.5-300	319.5-320	329.5-330	339-339.5	359.5-360	369.5-370	409.5-410	439.5-440	449.5-450	459.5-460	469.5-470.5	479.5-480	489.5-490	499.5-500	519.5-520	538-538.5	577.5-578	607.5-608	645-645.5	649.5-650	659.5-660	679.5-680	689.5-690	701-701.5	719.5-720	739.5-740	765.5-766	771-771.5	779.5-780	787.5-788	800.5-801	813-814	858.5-859	869.5-870	879.5-880	889.5-890	909.5-910	919.5-920	929.5-930	939.5-940	949.5-950
PLANKTONIC POPULATION (%)	2900	5000	7100	1600	7500	1500	9300	2800	4900	6000	2000	4200	1600	5100	2700	1100	590	2000	8000	520	560	6500	120	550	2200	2600	2400	1400	1900	570	2200	930	5400	1400	1000	31000	530	4200	3800	780	1600	4000	57000	87000	28000	4200	4400	11000	6200	6700	5100	3800	1100
Globigerina bulloides	9	13	11	7	15	14	17	[illegible]	16	7	17	12	5	11	7	12	10	6	14	16	9	9	6	8	7	[illegible]	2	7	6	23	.2	26	36	.6	1	25	20	5	7	4	6	20	9	3	35	18	7	12	26	2	8	11	22
digitata								3	1		1				3			4		1					2	[illegible]	3	2	2								.4								.5	2	2			.5	.6		5
eggeri	16	20	.9	11	18	12	15	24	.9	.3	7	24	6	23	33	13	[illegible]	.7	23	32	31	25	3	10	7	5	5	11	.9	11	1	11	16	28	7	47	6	35	2	22	6	33	64	63	18	8	7	22	3	1	3	2	1
inflata	1					1	21	6	19	5	23	12	16	6	2		7	5	4	.4		13	8	.4	4	5	.3		.4		12	7	9		5		9	6	24	20	18	14			3	14	7	6	.3	7	13	6	14
pachyderma	11	.1	12	15	18	8	5	2	3	3	2	3	1	3	[illegible]	[illegible]	[illegible]		5		2	8		.7	2	3	.7		1		3	27	11	21	2	2	.4			10	1	5	6	4	27	2				2	2	1	4
quinqueloba	1	12	9	2	13	9	0	7	11	29	6	10	2	2	.6		1	.6	2	10	4	3		21		6	.3	2	1		2	[illegible]	3	13	23	22		.4	4	.3	.5	7	15	16	2	1			.3		1	1	
radians		.3			1	.3														1		.5		4				3	.4	1			3						.4														.5
Globigerinella aequilateralis	.3						.5		.5				2	3	2	7		2	3	2	3		2	7	2	[illegible]	.3	2	1	3	1					.4		.4	5		1					1	1	3	1	2	1		.5
Globigerinita glutinata	5	9	9	7	7	9	3	.4	4	14	10	1			3		.3	4		2	.4	3	[illegible]	20	2	[illegible]		1		7	3	1	10	5	9			1	3	2		3	3	3		1	2	3	11	2	5	1	7
Globigerinoides conglobata													7												.4	2					2	12																					
rubra, etc	35	22	25	48	17	29	20	46	17	11	12	33	56	41	21	49	62	57	42	18	27	6	40	13	65	69	68	69	59	37	38	10	4	.6	23		52	22	39	31	38	12	1		5	33	59	41	50	61	62	73	36
(typical G. rubra present)							x							x	x				x	x	x	x		x	x	x	x	x	x	x								x	x	x	x					x	x	x	x	x	x	x	
sacculifera	.3						.3		5				2						1						1	1	5		6	5	5							8	8	6	4									1	.6		
tenella			.4	5		3			.5	3	2		.5	2	7			3	1	7	2	2		3	1			2	2	3	10	.4		.3	1			.4							.7			1	3	2	.3		2
Globorotalia scitula	10	12	14	9	11	10	7	2	6	15	13	4	1	1	7	6	5	1	1	8	7	8	2	17	1	1		3		4	8	4	7	13	14	.6	2		2	.3	1	4			4	5		3	.3		1	2	10
truncatulinoides	1								.5					1						4	.4		19	.7													8	9		.3	23					15	8	.6	4	13	.6	2	
Hastigerina pelagica																				.4				.4																													
Orbulina universa	.3					4	1	.3	2		7	1	1	7	10	11		4	3	.4	14	2	14	1	5	7	5	.3	2	6	3		.3	9	4	3	2	12	9	4	1	2	2	1	4		7	8	1	6	1	.4	
BENTHONIC POPULATION (actual numbers)	16	24	60	16	33	13	43	45	49	22	14	63	7	8	0	0	11	7	12	16	9	91	0	33	2	3	2	3	2	0	17	3	8	3	21	11	2	0	3	0	7	8	0	0	27	11	10	9	0	4	5	0	10
Articulina tubulosa & vars		1	5		6	3	6	29	17	4	3	19	4				5	3			1	77		1	1			1			1	1	2		1	1			3			2			6	1	4	7		1	1		5
Bolivina dilitata dilitatissima	1																			2	2			1																													
Bulimina costata		1								1		1							1					1							1		1		10																		
exilis																					1															2																	
gibba							4							1					2	1																																	
marginata									1			1								6				1											1																		
Cassidulina carinata	1	3	4	2	3	1	1					6																																									
cf. sicula								8	9	4	2	7												5										1																	2		1
Chilostomella mediterranensis																				2				2																		1			1			1					
Cibicides aff floridanus	1		6	1	2		3		1	2																																											
kullenberg																			1																		1								12	8							
Eggerella bradyi, etc									1																																	1					2			1	2		
Globobulimina affinis												1		3								4																			3				2								
? sp																																				5																	
Gyroidina delicata																																	1			1						1											
cf. neosoldanii			1											2					3		1							2													2				1			1		1			
Hoglundina elegans																		2																																			
Loxostomum alatum																								2																													
Miliolidae	4	4		8	2	4	3	1	6		1	7					2		2					2	1	2	1				4	1	1	2	1										2								
Miliolinella circularis	2	3	3	1	1		4	4	7	5	1	19	2				2							2			1																										1
Pseudoeponides umbonatus var																			1												5					2																	
Pullenia quinqueloba						1	1																																						1								
Pyrgo anomala																				1											3				3																		
lucernula	1		2		1		6	1	1	1	2			2																																							2
murrhina		4	10	2	4		2		1																																	1											
Quinqueloculina aff lamarckiana	4	4	22		12	1	9		1	4																																											
Robertina translucens			1			1	1																																						2	1	1			1			
Robulus spp																			1			1													1																		
Spiroloculina canaliculata			1								1							1																																			
Spirophthalmidium acutimargo		2			1							1																																			1						
Miscellaneous spp.	2	2	4	2	1	1	3	2	4		4	1	1				2			3	1	8		11		1			2		2	1	3		4		1				2	2			2	1	1						1
spp listed elsewhere			1			1				1								1	1	1	3	1		5							1																1						

TABLE 8. Distribution of Foraminifera in selected samples from Core 187.

CORE 188

SAMPLE	1	2	6	7	8	9	10	15	18	19	20	22	25	26	29	36	37	39	40	41	42	44	45	51	52	54	58	63	65	66	67	68	69	70	73	78	79	83	84	86	90
DISTANCE FROM TOP (CM)	2-2.5	9.5-10	49.5-50	59.5-60	69.5-70	79.5-80	89.5-90	139.5-140	169.5-170	179.5-180	191-191.5	209.5-210	239.5-240	252-252.5	279.5-280	349.5-350	359.5-360	379.5-380	392-392.5	399.5-400	409.5-410	429-429.5	438.5-439	499.5-500	511-511.5	528.5-529	559.5-560	609.5-610	629-629.5	639.5-640	649.5-650	659.5-660	669.5-670	679.5-680	709.5-710	759.5-760	769.5-770	808.5-809	819.5-820	839.5-840	879.5-880
PLANKTONIC POPULATION (%)	2600	1000	390	1400	4700	3500	6400	7400	480	1600	5600	2100	1700	3700	3400	14000	3200	4700	1600	4000	9700	500	3100	290	4300	5400	510	2000	3900	1900	1800	860	8800	600	47000	220	400	6500	20000	1100	13000
Globigerina bulloides	3	5	6	7	4	14	6	13	1	10	4	20	23	13	15	29	17	8	3	13	18	8	32	7	13	11	5	10	7	7	6	5	16	39	15	14	4	29	27	30	29
digitata	2	.4							3	1		4		2				1	.3	5	.3	.4							6	1					2						
eggeri	6	2	6	6	2	13	13	16	1	9	9	15	14	12	2	29	27	13		13	29	24	24	9	25	17	2	21	12	16	13	23	19	4	22	28	3	15	15	18	14
inflata	10	4	5	15	27	6			51	13	4	11	13	26	30	11	10	12		7	8	1		5	1	1	3	16	5		1	26	17		1	.5			2	5	3
pachyderma	2	2	1	6	.3	10	23	10		1	.7	.4	1	2		7	4	1			2	.4	1			2		1	.4		.4		5		1	3	.3		18	28	18
quinqueloba	.3	.6	1		.7	2	2	16	.4	7	27	21	10	6	30	4	16	7	.3	2	6	6	.3					8	1				2	5	2	6	.5		2	5	11
radians			3	5																											1			1	.3			.5	1		.3
Globigerinella aequilateralis	3	6			.3				1										19	7	2	1	3	2	.6	4	2		2	10	10				2	1	.7	2			
Globigerinita glutinata	6	13	12	13	.7	4	10	8	1	10	9	11	11	3	3	1	2	.7			.3							1	1	1	.4	7	3		2	3	.5	1	2	11	15
Globigerinoides conglobata																		3				.4																			
rubra, etc	52	44	62	33	56	41	31	17	6	7	27		13	19	14	14	18	46	64	49	19	24	35	50	41	50	67	41	61	48	47	30	32	5	37	36	84	37	15	.4	3
(typical G. rubra present)	x	x	x		x																	x	x	x	x	x	x								x	x	x	x			
sacculifera	12	15																												16	11				1		4				
tenella	.3	2	3	3	.3					2	.6		2	9	.5		.3	3	2	1	5	4	1	1	9	1	1		2			4	3	1	8	2	.5	5			.3
Globorotalia scitula		1				9	15	20		18	18	21	5	2	5	5	3	3			5	23		1	3	7	.4	2			3	2	3	9	4	5	.5	8	17	.6	3
truncatulinoides	.6		.3	11	8																3			23			15								.3	.5					
Hastigerina pelagica	.3																														.4										
Orbulina universa	3	5		1					35	22			8	6			2	2	11	2	2	7	3	2	7	7	4		2	1	6	3		36	2	1	2	2	.5	2	3
BENTHONIC POPULATION (actual numbers)	1	0	5	8	8	50	57	31	4	15	17	4	3	10	46	59	3	153	0	3	5	0	0	5	0	10	2	1	3	3	3	2	0	0	1981	6	2	0	14	11	20
Angulogerina angulosa																																			15						
Articulina tubulosa & vars.				4	4	8	8	8		6	10	4	1	5	35	43	2	142		3	2			2		4	1	1	1						42					1	5
Biloculinella labiata																																			6						
Bolivina albatrossi																																			223	1					
attica																																			5						
difformis																																			2						
dilitata dilitatissima																																			446						
pseudoplicata																																			11						
Bulimina costata																																			125		1				2
exilis																																			25						
gibba																																			11						
marginata																																			256	2					
Cassidulina carinata																																			70						
crassa																																			20						
cf oblonga																																			4		1				
cf sicula				1		1	7				1		1	2	2	5					1														24	1					
Chilostomella mediterranensis			3																																16						
Cibicides kullenbergi																																			4						
Eggerella bradyi, etc																																			6						
Elphidium spp																																			4						
Epistominella rugosa convexa																										6															
Gavelinopsis praegeri, etc																																			66						
Globobulimina affinis			1																		2			1								2			4						
Gyroidina delicata																																			10					1	1
cf neosoldanii																								1			1		1	2	2				47						
umbonata																																			5						
Hanzawaia rhodiensis	-																																		29						
Hoglundina elegans																																			9						
Hyalinea balthica																																			103						
Lagenonodosaria scalaris																																			10						
Loxostomum alatum																																			18						
Miliolidae			1	1		3	1	1	1	1			1		2	2		1											1	1					85	1			8	7	9
Miliolinella circularis				1		15	13	3	1	5	1				5	8	1	4																	16						
Neoconorbina terquemi																																			2						
williamsoni																																									
Nonion barleeanum, etc																																			33						
Planorbulina mediterranensis																																			3						
Pseudoeponides umbonatus var																																			11						1
Pullenia quinqueloba																																			12						
Pyrgo lucernula					3		1		2					2	1																										
murrhina						18	16	2																															3	1	
Quinqueloculina aff. lamarckiana						1	5	15			2																								5						
Robertina translucens																		1																	3						
Robulus spp.						1								1																					9						
Rosalina aff. columbiensis																																			3						
globularis bradyi																																			2						
obtusa																																			4						
spp																																			23						
Sigmoilina tenuis																																			4						
Sphaeroidina bulloides																																			2						
Spirillina vivipara																																			3						
Spiroloculina angulosa																																			4						
canaliculata																																			7						
grata																																			7						
Spirophthalmidium acutimargo							1																												2						1
Streblus beccarii & vars.																																			4						
Uvigerina mediterranea																																			28						
peregrina																																			14						
Valvulineria complanata										1																									3						
Virgulina mexicana																																			9						
Miscellaneous spp				1		2	5	2		1	2				1	1		5						1							1				57				3	1	1
spp. listed elsewhere	1					1				1	1																								10	1					

TABLE 9. Distribution of Foraminifera in selected samples from Core 188.

CORE 189

SAMPLE	1	2	7	11	12	13	14	16	17	18	19	20	21	22	23	25	26	27	28	29	30	31	33	34	36
DISTANCE FROM TOP (CM)	2.5-3	9.5-10	59.5-60	99.5-100	109.5-110	119.5-120	129.5-130	149.5-150	159.5-160	169.5-170	179.5-180	189.5-190	199.5-200	209.5-210	218-218.5	224-224.5	228.5-229	239.5-240	249.5-250	259.5-260	268.5-269	281.5-282	289.5-290	299-299.5	319.5-320
PLANKTONIC POPULATION (%)	2300	7400	7200	4900	5300	4700	1400	2300	4300	3100	8400	8400	3300	6700	13000	10000	8800	6000	3300	2400	5800	23000	4800	3400	2900
Globigerina bulloides	10	12	29	23	15	23	7	10	.0	43	23	8	11	15	12	19	14	6	15	19	9	15	14	15	11
digitata	2		.4				4	4	2		4			2	5	1			9	.7	3			4	1
eggeri	5	12	11	5	9	6	4	2	12	6	20	2	7	7	27	22	26	6	5	9	20	66	4	2	
inflata	1			9	8	7	29	14	16	13	9	5	11	10	4	.3		4	12	3	10	3	19		
pachyderma	1	18	17	2	3	2	1		9	1	6		.5	2	3	.3	2		2		4	.3	.3		
quinqueloba	2	2	6	18	14	16	4	4	5	25	16	4	2	2				1	1	4	1	7	.7		.3
radians			.6																			.3			
Globigerinella aequilateralis	3							1					3	3	3	2	1	1	2	8	7		4	4	3
Globigerinita glutinata	4	8	5	15	15	11	6	2	2	2	1				2		.4	5		.7	5	.6		.5	.3
Globigerinoides conglobata																							4	3	1
rubra, etc	57	33	14		19	20	18	44	33	4	14	80	50	44	22	18	45	78	46	43	26		34	60	60
(typical G rubra present)	x														x	x	x				x			x	x
sacculifera	10																							.7	6
tenella	2	.4			2	.3	4	5	4	.3			1	3	7	22	2		3	3	4	.4	5	4	14
Globorotalia scitula	1	14	17	28	15	14	5	1	3	5	4	1	7	2	10	2	5	3	1	.3	7	5	2		
truncatulinoides														5	5					1					
Hastigerina pelagica							.3						1					.3	1	1				.7	1
Orbulina universa	2						17	13	4		3		6	5	9	13	4		3	7	6	2	13	6	2
BENTHONIC POPULATION (actual numbers)	2	30	41	11	14	27	16	10	54	136	121	95	21	61	49	0	0	2	9	2	24	0	1	1	4
Articulina tubulosa & vars		10	13	7	8	5	5	3	17	77	72	52	6	54	26			1	8		22			1	2
Bulimina aculeata																									
costata																									
exilis																									
Cassidulina carinata		1		1						4															
cf sicula		1			1	3	3	2	5	7	12	1													
Cassidulinoides tenuis																									
Chilostomella mediterranensis														1	7										
Cibicides aff floridanus					1					2															
kullenbergi																									
Eggerella bradyi, etc																									
Epistominella rugosa convexa														1											
Gavelinopsis praegeri, etc																									
Globobulimina affinis															14						2				
? sp																									
Glomospira charoides												2		1											
Gyroidina delicata																									
cf neosoldanii														3				1		2			1		1
Miliolidae		2	1	1	2	1			1	1	2	2	1												
Miliolinella circularis		3	5	1	1	6	8	5	23	36	34	33	14												
Pseudoeponides umbonatus var.																									
Pullenia bulloides																									
quinqueloba																									
cf riveroi																									
Pyrgo anomala																									
lucernula	1																								
murrhina	1	7	7																						
serrata																									
Pyrgoella sphaera																									
Quinqueloculina aff lamarckiana		4	9		1	1																			
Robertina translucens		1							4	2															
Robulus spp										2															
Spiroloculina canaliculata									1	1		1													
Spirophthalmidium acutimargo			2							1	1														
Virgulina complanata																									
mexicana																									
Miscellaneous spp		1	4	1		1			3	3		4		1	2				1						1
spp listed elsewhere																									

SAMPLE	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	55	56	57	58	59	60	61	62
DISTANCE FROM TOP (CM)	329.5-330	339.5-340	350.5-351	359.5-360	369.5-370	379.5-380	388.5-389	399.5-400	409.5-410	419.5-420	429.5-430	439.5-440	449.5-450	459.5-460	469.5-470	479.5-480	489.5-490	509.5-510	519.5-520	527.5-528	532.5-533	539.5-540	549.5-550	559-559.5	569.5-570
PLANKTONIC POPULATION (%)	24000	3900	5300	7800	9400	11000	4600	6700	5400	1800	23000	42000	29000	5700	12000	6100	4000	21000	46000	46000	22000	5300	27000	9500	6100
Globigerina bulloides	7	38	9	27	20	26	26	16	14	9	5	26	20	15	8	20	31	12	16	3	19	12	.0	17	18
digitata	1					.6		.5		2				.3			2				1	5		.3	
eggeri	11	20	3	16	19	19	18	21	33	13	66	28	38	3	59	12		26	52	67	24	3	18	[illegible]	5
inflata			12	2	3	6				4	1		2	10	7		1	11	1		7	11	4	3	10
pachyderma			5	15	13	22	14	15	15	[illegible]	4	1	14	6	1		2	2	3	2	16	.4			3
quinqueloba	2	1	.6	6	3	7	17	11	9	14	15	41	7	1	2	5	1	4	22	26	6	.6	2	2	5
radians	2		.3		1																				3
Globigerinella aequilateralis	3	.6	4											2	.3	4		1				1	6	4	.3
Globigerinita glutinata	12	2	11	3	5	5	16	8	4	5	1		5		.3	11	1	3	1		5	1	6	12	5
Globigerinoides conglobata			1	5																					
rubra, etc	40	29	32	8	20	2			10	35	1		2	44	13	20	37	26	1		9	40	38	55	22
(typical G rubra present)	x	x	x												x	x		x	x				x	x	
sacculifera	1		12												1		2	5							
tenella	16	8	5	7		3	1		.4	.5	.3			14	4	3	6	1			5	2	7	5	13
Globorotalia scitula	3	1	3	11	16	5	8	12	4	7	6	2	8	.3	1		13	1	.3	2	4	.3	1	.3	5
truncatulinoides										1				5	1	5		5			.6	18	.6	3	1
Hastigerina pelagica														.3							.3	.3			
Orbulina universa	4		4			4		16	10	7		3	4	[illegible]	2	20	4	3	3		3	5	7		2
BENTHONIC POPULATION (actual numbers)	4	0	5	49	4	18	18	7	20	58	257	0	163	5	25	0	24	9	10	0	174	11	50	5	38
Articulina tubulosa & vars	1				1	10	10	3	5	44	1		18	3	1		15	4	1		161	7	25		19
Bulimina aculeata																									
costata						1	1		2	4															
exilis										2	50														
Cassidulina carinata							1																		
cf sicula																									
Cassidulinoides tenuis											60														
Chilostomella mediterranensis			1								3							1	5				9		
Cibicides aff floridanus													1												
kullenbergi													17								3				
Eggerella bradyi, etc													40		4		2								
Epistominella rugosa convexa																	1								
Gavelinopsis praegeri, etc													3												
Globobulimina affinis															20										
? sp											86														
Glomospira charoides																									
Gyroidina delicata			1	6							40		64					1							
cf neosoldanii	2												1								1		1		
Miliolidae				12	2	5	3	1	4	3				1			2								10
Miliolinella circularis				4					1															1	
Pseudoeponides umbonatus var.			3	12							16		12	1					1						
Pullenia bulloides																									
quinqueloba						1					1							1	2				1		
cf riveroi																					1				
Pyrgo anomala				1				1	2																
lucernula									2	1			1				2							2	
murrhina																			1						
serrata																									
Pyrgoella sphaera				1		1		2		1															
Quinqueloculina aff lamarckiana				4																					
Robertina translucens				1									1				1				3	2			4
Robulus spp							1																		
Spiroloculina canaliculata																									
Spirophthalmidium acutimargo				2	1																				
Virgulina complanata				1																					
mexicana																					3		14		
Miscellaneous spp	1			5			2		3	3			5				1	2			2	2		2	5
spp listed elsewhere									1																

SAMPLE	63	65	66	67	68	69	70	71	72	73	74	75	76	77	78	80	81	83	84	85	86	88	89	90	91
DISTANCE FROM TOP (CM)	579.5-580	599.5-600	607.5-608	617-617.5	622-622.5	629.5-630	639.5-640	649.5-650	659.5-660	669.5-670	678-678.5	683.5-684	689.5-690	699.5-700	709.5-710	729.5-730	739.5-740	759.5-760	769.5-770	779.5-780	789.5-790	809.5-810	818-818.5	829.5-830	839.5-840
PLANKTONIC POPULATION (%)	3200	6800	2800	6600	3900	6000	3900	14000	1900	4100	4000	13000	6200	28000	2700	5000	4500	11000	6000	24000	11000	2200	7800	9600	4400
Globigerina bulloides	32	25	13	11	13	27	16	19	2	4	12	16	12	34	14	10	15	9	14	25	18	14	[illegible]	25	22
digitata	3	1	.3	5	1	1		1			1	.5	.5				1	.3	2	1	.3	[illegible]	4	3	1
eggeri	.5	16	1	5	2	4	.4	16	.4		5	1	10	20	4	4	1	12	3	25	37	.3	13	4	9
inflata	12	11	13	14	15	19	.6	.6	10	17	23	2	16	7	9	8	4	11	10		1		14	.0	4
pachyderma	1	.8	1	5	1	2	.4	9					3	11	3	1		.6	1	16	17	5	2	2	4
quinqueloba	4	5	1	2	1		1	3	.6			1	1	6	19	1	1	.6	1	18	6	1	.4	1	5
radians	.5										.5	1	.5						.3						
Globigerinella aequilateralis				6	3	2	2	2	10	2	7	3	3	2		3	2	2	5			2	1	2	3
Globigerinita glutinata	5	1			2	4	[illegible]	1	4	.4		12	3	4	2	4	1	2	11	11	4	1	2	3	7
Globigerinoides conglobata																		.6				3			
rubra, etc	27	2	60	25	26	21	48	18	59	64	36	43	41	6	4.	29	55	27	32	1	4	46	26	30	31
(typical G rubra present)				x	x			x	x		x	x	x	x	x			x	x				x	x	x
sacculifera										3								9	.3			.4	3	10	1
tenella	.5		3	10	21	8	7	6	4	6	5	14	3	4	3	7	2	5	13	.3	5		4	3	7
Globorotalia scitula	3	14	4	2	9	8	6	3					1			5	4	5	3		7	3	2	5	2
truncatulinoides			1					2	12		8	.3			4	23	12	11				3	9		1
Hastigerina pelagica										.4	.5											.4			
Orbulina universa	11	7	2	5	6	4	2	4	1	3	2	6	6	6	1	5	5	4	4	2	.3	3	6	4	3
BENTHONIC POPULATION (actual numbers)	7	31	12	8	19	102	8	15	2	4	9	0	31	1349	32	5	16	6	0	1020	106	24	8	28	26
Articulina tubulosa & vars	3	17	11		9	79	7	12		4	[illegible]		1	26	1	2	6			2	15	4	5	6	1
Bulimina aculeata											1		25	1280				5		896					
costata													1		1										
exilis																									
Cassidulina carinata																									
cf sicula																				1					
Cassidulinoides tenuis																									
Chilostomella mediterranensis				4	1													1			1				3
Cibicides aff floridanus																									
kullenbergi					4	16																2			1
Eggerella bradyi, etc					1										1										
Epistominella rugosa convexa																									10
Gavelinopsis praegeri, etc																									
Globobulimina affinis					1																1			1	5
? sp																									
Glomospira charoides																									
Gyroidina delicata														3						7					
cf neosoldanii					1		1	1	2				1				1			1	2	1	1	4	1
Miliolidae	1	1												19	3										
Miliolinella circularis														2	17										
Pseudoeponides umbonatus var.													3				7			1	12	15	2	12	
Pullenia bulloides																								2	3
quinqueloba						1																			
cf riveroi		1				1																			
Pyrgo anomala														4		1									
lucernula	1		1		1																				
murrhina		9												12	5					11	32				
serrata																				80	38				
Pyrgoella sphaera																									
Quinqueloculina aff lamarckiana																									
Robertina translucens																									
Robulus spp																									
Spiroloculina canaliculata																									
Spirophthalmidium acutimargo														1	1						1				
Virgulina complanata				2		1		1						1			2			11	1				
mexicana				2	1	2																			
Miscellaneous spp	1	3				2		1						1	3	2				10	2	2		3	2
spp listed elsewhere	1																				1				

TABLE 10. Distribution of Foraminifera in selected samples from Core 189.

CORE 190

SAMPLE	1	5	6	8	9	11	13	16	17	18	20	21	22	23	25	26	27	28	29	30
DEPTH FROM TOP (CM)	1-1.5	39.5-40	49.5-50	69.5-70	79.5-80	91.5-92	109.5-110	139.5-140	149.5-150	161.5-162	179.5-180	189.5-190	199.5-200	209.5-210	219.5-220	222.5-223	231.5-232	239.5-240	249.5-250	259.5-260
PLANKTONIC POPULATION (%)	4700	7500	22000	7300	5700	7600	1700	13000	3600	11000	5900	7900	2000	5600	6900	11000	8300	5200	4900	2300
Globigerina bulloides	12	20	20	.5	17	13	4	17	17	42	6	12	15	.	12	8	1	9	17	24
digitata							5		3	3			4	5		.	2		8	
eggeri	14	14	22	15	13	9	3	.6	3	9	.	6	1	8	21	30	8	5		
inflata					8	5	40	16	.1	4		20	1	5	9	3	10	8	6	2
pachyderma	19	13	12	8	2		7	6		3				3	6	2	3	.6		
quinqueloba	4	23	9	4	23	.	1	26	14	14	18	8	.	3	1	.	4	6	3	1
radians													1						3	1
Globigerinella aequilateralis				.4			1						5	7	5	4	4	3	1	.0
Globigerinita glutinata	12	14	6	8	.5	15	3	2	2	1		1			6	2		2	.	4
Globigerinoides conglobata																				
rubra, etc	25	2	20	23		24	15	15	38	21	74	47	62	44	23	25	39	55	60	40
(typical G rubra present)																	x			
sacculifera						7						1								
tenella				2	3		4					1	6	5	10	9	6	1	3	14
Globorotalia scitula	14	14	11	13	21	15	1	2	4	5	3	4		3	1	10	7	3	5	
truncatulinoides									.4					4			8		3	4
Hastigerina pelagica													4	3						4
Orbulina universa				1			22		7				7	4	6	7	5		2	6
BENTHONIC POPULATION (actual numbers)	24	41	109	45	33	20	21	110	26	113	120	40	8	15	19	3	1	2	5	3
Articulina tubulosa & vars	1	19	18	26	..	8	2	80	15	79	83	87		10	19	2		2		
Bulimina aculeata																				
costata		1	2	1	1					1										
Cassidulina carinata	4																			
cf sicula		1	1		1			6	1	8	1									
Cassidulinoides tenuis																				
Chilostomella mediterranensis																				
Cibicides kullenbergi																				
Eggerella bradyi, etc	1																			
Globobulimina affinis																				
Gyroidina delicata																				
cf. neosoldanii														4					3	3
Miliolidae	2		5	2	2	1	4	5	2	3	3	2								
Miliolinella circularis	1	3	9	11	1	7	19	14	5	19	33	50	4						2	
Pseudoeponides umbonatus var																				
Pullenia quinqueloba													2	1						
cf riveroi								1		1										
Pyrgo anomala	3																			
lucernula							1													
murrhina	8	6	30		10															
Pyrgoella sphaera			1																	
Quinqueloculina aff lamarckiana	1	6	38	5	5	2														
Robertina translucens									1	1										
Robulus spp			1																	
Virgulina complanata																				
Miscellaneous spp	3	4	2		2	2		4	1			1	2			1				
spp listed elsewhere		1	2				1		1	1										

SAMPLE	31	32	33	34	35	36	39	40	42	45	46	48	49	50	51	52	54	55	56	57
DEPTH FROM TOP (CM)	269.5-270	279.5-280	289.5-290	299.5-300	309.5-310	319.5-320	349-349.5	359.5-360	379.5-380	409.5-410	418.5-419	439.5-440	449.5-450	459.5-460	469.5-470	482.5-483	499.5-500	505-51	519.5-520	529.5-530
PLANKTONIC POPULATION (%)	12000	31000	4200	3200	2600	1800	5700	4600	7800	8700	4100	1600	1800	8200	20000	18000	49000	20000	23000	1600
Globigerina bulloides	1	20	18	21	16	15	19	16	28	31	16	23	19	11	5	4	20	13	16	25
digitata	1		2		1	2							.5	1	3				3	
eggeri	22	44	1		1		1	8	20	21	28	5	2	15	62	64	45	43	21	5
inflata	7		4					12	3	9		7	6	7	1			4	10	15
pachyderma	2							5	.3	6	8	3	1	1	10	4	1	8	3	
quinqueloba	3	18	.4				3	1	3	6	22	10	10	5	15	23	30	17	.2	5
radians						.4	1	.4		2		.7	5					3		
Globigerinella aequilateralis	7			2		6	2			4										
Globigerinita glutinata	4			1	2	4	2	2	2	9	7	10	15	6	1			3		
Globigerinoides conglobata								4												
rubra, etc	29		73	66	63	54	51	36	11	2	1	34	29	30	2		.3	3	13	26
(typical G rubra present)							x	x						x						
sacculifera					6	7	7													
tenella	6	4	6	6	6	11	11	5	.4	4			1	1	.6			.7	1	2
Globorotalia scitula	10	15	1		6		2	7	19	7	13	4	10	7	3	8	2	6	12	13
truncatulinoides												3		4						11
Hastigerina pelagica				.5	.3															
Orbulina universa	4	2		3	4	4	3	3		2	5		6	6			1	4	1	3
BENTHONIC POPULATION (actual numbers)	0	0	1	3	1	1	0	26	32	11	5	23	19	32	267	1	0	162	25	6
Articulina tubulosa & vars			1									1		15	200			34	4	1
Bulimina aculeata																				
costata										1	1	2	5	2	1					
Cassidulina carinata																				
cf sicula																				
Cassidulinoides tenuis															8					
Chilostomella mediterranensis															1					
Cibicides kullenbergi																		18	1	
Eggerella bradyi, etc															2			29	5	1
Globobulimina affinis															1					
Gyroidina delicata															17			44		
cf. neosoldanii				2		1														
Miliolidae								1	7	6		8	2	6				4	3	3
Miliolinella circularis				1	1			9	4		1	2							2	
Pseudoeponides umbonatus var								2					1	2	35			21		
Pullenia quinqueloba								1												
cf riveroi									1		1									
Pyrgo anomala																				
lucernula												1						1	4	1
murrhina								3	8											
Pyrgoella sphaera									4	2	1	6	3							
Quinqueloculina aff lamarckiana								7	3	1		1	7							
Robertina translucens										.								1		
Robulus spp									1									1	1	
Virgulina complanata																			4	
Miscellaneous spp								2	3	1	1	1	1	7	1			7	1	
spp listed elsewhere								1	1			1			1	1		2		

SAMPLE	58	59	60	61	62	63	64	65A	65B	66A	66B	67	68	70	71	72	73	74	76	77
DEPTH FROM TOP (CM)	539.5-540	550-550.5	560-560.5	571-571.5	579.5-580	589.5-590	599.5-600	609.5-610	6[illegible]9.5-610	619.5-620	619.5-620	629.5-630	639.5-640	659.5-660	669-669.5	679.5-680	689.5-690	699-699.5	719.5-720	729.5-730
PLANKTONIC POPULATION (%)	2800	4900	3[illegible]00	5500	2300	9600	12000	36000	2400	37000	4400	5000	6500	19000	8400	3[illegible]00	6[illegible]00	2900	4700	9200
Globigerina bulloides	17	25	9	17	22	6	20	8	5	.5	12	28	8	14	30	7	28	24	22	18
digitata	1	.	5	1	3	2			2		4		4	2			3	2	.	2
eggeri	1	14	32			6	33	56	26	65	23	30	4	.8	2	4	5	4	5	16
inflata	2	32	10	14		1	17	4	.3		13	7	18	5	4	3	17	12	16	14
pachyderma			2	.3		7	3	3	1		5	9	4	1		5	3	6	2	12
quinqueloba	6	1	1	1	4		4	30	7	33	11	8	1	1	.	2	.0	6	7	4
radians																1				
Globigerinella aequilateralis	3		2	2	5	9	2		1		1		1	7	3		1	2	1	
Globigerinita glutinata		3	5	3	6	10	5	1	3		5	4	2	6	10	4	9	9	6	5
Globigerinoides conglobata																				
rubra, etc	56	14	26	30	56	28	7		26		17	7	41	31	41	63	8	21	27	13
(typical G rubra present)			x	x		x	x		x		x			x	x		x	x		
sacculifera					3	19	.5		2		5									
tenella	9	3	6	7	1	2	1		2		4	5	3	7	6	.5	3	2		1
Globorotalia scitula	1	5	5	4	4	7	2		1		4	1	6	3		3	14	10	12	10
truncatulinoides	4	1	4	19	1	3			8		4		14	1	4		3			
Hastigerina pelagica	.6			.3	4													.3		
Orbulina universa	4	3	2	4	1	5	5	1	3	1	2	1	3	4	1		.5	7	1	5
BENTHONIC POPULATION (actual numbers)	2	57	2	3	3	12	18	0	9	0	1	5	3	189	0	28	60	15	55	16
Articulina tubulosa & vars		43			1		3		3				1	153		7	36	5	22	4
Bulimina aculeata																				
costata																				
Cassidulina carinata																				
cf sicula																				
Cassidulinoides tenuis																				
Chilostomella mediterranensis						12	2					4		33			1			
Cibicides kullenbergi																				
Eggerella bradyi, etc		8																		
Globobulimina affinis		4	2				4													
Gyroidina delicata							2		2											
cf. neosoldanii																				
Miliolidae					1											1	1	1	9	3
Miliolinella circularis	1															16		1	8	
Pseudoeponides umbonatus var																				
Pullenia quinqueloba									2		1									
cf riveroi							1							2		1			1	
Pyrgo anomala																				
lucernula				1									1					6	2	1
murrhina							4										12	1	3	1
Pyrgoella sphaera																				
Quinqueloculina aff lamarckiana																	2		6	1
Robertina translucens		1		2	1							1				1	4			
Robulus spp							2		1								1			1
Virgulina complanata																				
Miscellaneous spp	1	1							1							1	3		4	5
spp listed elsewhere													1	1		1				

SAMPLE	78	79	81	82	83	84	86	87	88	89	90	91	92	93	94	96	97
DEPTH FROM TOP (CM)	739.5-740	749.5-750	768-768.5	779.5-780	789-789.5	799.5-800	819.5-820	831.5-832	839.5-840	849.5-850	859.5-860	869.5-870	879.5-880	889.5-890	899.5-900	919.5-920	929.5-930
PLANKTONIC POPULATION (%)	9400	1000	3800	2600	4800	5900	5900	5500	5000	5200	6800	44000	7300	3800	2600	7100	3000
Globigerina bulloides	3	21	19	8	2	28	7	7	.2	7	.2	47	14	6	.	8	58
digitata			3	2	1	1	3	1	1		5		.4			2	1
eggeri	.1	15	2	3	18	3	2	10	3		9	20	2	6	5		
inflata	.7	3	26	.8	7	.6	10	24	12	24	22	7	9	1	6	.8	
pachyderma	8	19		6	6	3	5	8	.	3	2	16		30	5		3
quinqueloba	6	3	1	3	3		2	3	2	.3	2	2	30	1	8		.5
radians		.3					3					3			.3		1
Globigerinella aequilateralis				7	4		13	5	4	5	3	1				2	6
Globigerinita glutinata	7		4	3		6	4	1	.6	1	2	1	2	2	2	.4	3
Globigerinoides conglobata																	3
rubra, etc		21	36	49	.8	18	34	34	40	50	37		26	3	42	45	22
(typical G rubra present)				x	x			x	x		x						
sacculifera										3							.5
tenella			1	9	5	3	12	4	2	8	7	.3	1	.4	3	4	2
Globorotalia scitula	15	15	7	3	1	.5	5	2	6		2	.3	2	10	6		3
truncatulinoides					3			6	16							.6	.3
Hastigerina pelagica																	
Orbulina universa	5	2	3	5	3	2	4	3	.3	1	1	5	2		1	4	4
BENTHONIC POPULATION (actual numbers)	29	12	1	2	3	25	1	1	2	1	4	785	18	12	8	2	1
Articulina tubulosa & vars	2	7	1		1	20	1	1		1		2		1			
Bulimina aculeata											2	768					
costata													1	1	1		
Cassidulina carinata																	
cf sicula													1				
Cassidulinoides tenuis																	
Chilostomella mediterranensis					1												
Cibicides kullenbergi																	
Eggerella bradyi, etc					1				1						1		
Globobulimina affinis																	
Gyroidina delicata												2					1
cf. neosoldanii																	
Miliolidae	5											1		2	1		
Miliolinella circularis		3											12	2			
Pseudoeponides umbonatus var											2				2	2	
Pullenia quinqueloba															1		
cf riveroi	2	1				2											
Pyrgo anomala												1					
lucernula																	
murrhina	13											6	2	2			
Pyrgoella sphaera																	
Quinqueloculina aff lamarckiana	4											2			1		
Robertina translucens																	
Robulus spp																	
Virgulina complanata												1					
Miscellaneous spp	3	1		2		3			1			2	2	4	1		
spp listed elsewhere																	

TABLE 11. Distribution of Foraminifera in selected samples from Core 190.

CORE 191

SAMPLE	1	2	3	4	5	7	10	11	13	14	15	17	18	19	20	22	23	26	27	28	29	30	32	33	34	36	39	40	41	43	44
DISTANCE FROM TOP (CM.)	3 - 3.5	9.5 - 10	18.5 - 19	25.5 - 26	31 - 31.5	45.5 - 46	68.5 - 69	76.5 - 77	96.5 - 97	106.5 - 107	116.5 - 117	139.5 - 140	145.5 - 146	154.5 - 155	163.5 - 164	184.5 - 185	194.5 - 195	219.5 - 220	229.5 - 230	240 - 240.5	246.5 - 247	255.5 - 256	274.5 - 275	279.5 - 280	289.5 - 290	309.5 - 310	339.5 - 340	347 - 347.5	350.5 - 351	361.5 - 362	367 - 367.5
PLANKTONIC POPULATION (%)	2000	3500	5500	2800	3300	6800	8000	19000	2100	1600	6400	1300	52000	3500	2500	3300	5000	3800	5800	1400	5200	3100	3000	2700	5100	1800	19000	21000	8800	5000	3500
Globigerina bulloides	10	15	28	18	19	28	15	21	22	15	8	6	9	23	11	13	7	22	24	11	17	18	20	12	8	13	41	33	8	4	2
digitata		1								2	.5	3			3	1	.3			1	.6	1	.5	1		4			1		
eggeri	9	21	21	20	20	22	26	23	7	8	30	14	63	5	19	12	16	11	3	2	10	2	.3	4	15	2		1	8	38	40
inflata	21	8	3	2	3	11	1	1	16	6	8	1	1	15	10	24	17	12	.6	20	14	16	19	10	19	5	4	3	15	26	24
pachyderma	2	6	19	20	21	18	20	33	.4	.5	.5			2	1	.7	6	32	34	2	5	3	2	4	14				4	8	10
quinqueloba	6	1	5	4	4	6	18	7	7	8	2	5	25	7	7	10	6	4	10	4	5	3	5	3	3	8	7	1	1	6	6
radians			.3	1	.5	1	.4		1	1		.6		.5						.3				1		1	2	1			
Globigerinella aequilateralis		2			.5					.5	1	5			1		.3			1		4		4	2	2	3	1	3		
Globigerinita glutinata	4	2	1	4	6	8	6	4	1	.5	.3	6	.4	4	9	5	6	1	1	2	6	10	12	8	2	2	7	11	3	2	3
Globigerinoides conglobata		2	3																				.5								
rubra, etc	34	27	6	15	13	.5		.5	25	38	27	46		28	25	23	32		16	36	21	31	16	35	18	57	22	35	43	2	
(typical G. rubra present)											×	×												×			×	×	×		
sacculifera		.4									5	5																			
tenella	2	5	3	1		1	1		1	1	3	2		.7			1			9	1	3	1	5	7	3	5	8	6		
Globorotalia scitula	3	3	9	15	12	3	10	6	13	3	3	1	.4	6	4	11	4	10	8	7	16	5	16	7	10	3			1	13	14
truncatulinoides		.4					.4		4	1	7	.3		6																	
Hastigerina pelagica												.3								.3											
Orbulina universa	8	5	.6		1	1	2	4	2	15	4	4	1	2	10		4	8	3	4	4	4	7	6	2		9	6	7	.3	.5
BENTHONIC POPULATION (actual numbers)	16	3	23	3	7	6	11	20	22	58	3	15	2	48	34	31	8	32	10	16	59	17	9	62	51	38	0	1	8	11	14
Angulogerina angulosa							1														1			1							
Articulina tubulosa & vars.	12	1	17	3	1	3	6	16	17	32	1	8		38	28	22	6	4	9	10	46	11	3	9	16	14					1
Bolivina difformis										1						1					1										
dilitata dilitatissima						1																		1	1						
pseudoplicata						2	2		2	5		1		3			1			4	2	1	1	7	3	1			1		1
Bulimina aculeata																														7	9
marginata										1														1	1					1	
Cassidulina carinata									1	1														1	2						1
crassa										1	1													3	1	2					
cf. oblonga													1				1					1		2							
subglobosa																								4							
Elphidium spp.										1				1										1		1					
Gavelinopsis praegeri, etc.																								3	1	2					
Gyroidina delicata								2																	1						
Miliolidae			1		3											4					1			4		2					
Miliolinella circularis	3																														
Neoconorbina williamsoni									1	4		3			1						1			2	1	4					
Nonion barleeanum, etc.																								3	1						
sp. B																1								1		1					
Planorbulina mediterranensis																								2	2						
Pseudoeponides umbonatus var.																								1					4	1	
Pullenia cf. riveroi																		1				1	1								
Pyrgo anomala																		3													
murrhina		1	1											1				22													
Robertina translucens										3				2	1																
Rosalina aff. columbiensis										1					1									2	1	1					
obtusa										1												1				2					
spp.												1													2						
Virgulina complanata														1											2	1			1		
Miscellaneous spp.	1		2		2			1	1	3	1	2		1	3	3			1	1	6	1	3	9	13	4			1	2	2
spp. listed elsewhere		1	2		1		2	1		4			1	1				2		1	1	1	1	5	3	3		1	1		

TABLE 12. Distribution of Foraminifera in selected samples from Core 191.

CORE 192

SAMPLE	1	3	4	5	6	11	16	21	22	23	24	25	26	28	29	30	32	33	34	36	37	38	39	40	41	42	43	46	48	49	53	54	56	57	58	60	62	64	65	66	67	69	71	76	[illegible]	79	[illegible]	[illegible]	82	83	84	85	87	88	89	[illegible]	[illegible]
DEPTH FROM TOP (CM)	1.5-2	4.5-5	24.5-25	34.5-35	44.5-45	89.5-90	139.5-140	193-193.5	199.5-200	209.5-210	221.5-222	229.5-230	239.5-240	259.5-260	271.5-272	278-278.5	290-290.5	299.5-300	309.5-310	329.5-330	342-342.5	349.5-350	362.5-363	369.5-370	379.5-380	389.5-390	[illegible]	[illegible]	428.5-429	438.5-439	478.5-479	488.5-489	509.5-510	519.5-520	529.5-530	549.5-550	571.5-572	593-593.5	598-598.5	609.5-610	619.5-620	639.5-640	659.5-660	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PLANKTONIC POPULATION (%)	[illegible]	[illegible]	[illegible]	2000	1800	4300	2000	2900	3600	6400	7900	3200	3400	500	5700	6400	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2400	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Globigerina bulloides	5	20	24	22	21	7	8	14	10	16	6	8	16	38	18	17	20	41	7	14	27	17	18	34	22	14	11	19	23	23	19	9	19	23	27	15	7	25	27	9	18	37	26	32	20	37	17	3	.4	4	30	.4	11	36	23	15	25
digitata	3			1								1	.3	2	1	.3			.5		1		5	5		1		2	6	4	1	5	2	3	2	1											.4	.5				2	.6	3	5		3
eggeri	4	.	3	11	6	13	8	11	7	11	10	3	5	4	1	12	4	1		2	6	11	4		14	23	20	4	2	1	9	21	1		.4	7	20	22	3	7	16	18	24	13	24	6	1	3	23	33	4	23	34	2	4	4	3
inflata	2	8	13	5			.4	2	5	7	9	5	21	21	23	17	17	.5	1	3	5	6	8	.3	8	13	12	15	3	7	1	8	4					.5		15	.3	6	4			.7	3	6	3	3	.6	7	5	.4	2	7	13
pachyderma	.	2	4	6	7	2	7	.	2	5	.4	5	4		.		5			1	.4	1	1	.	.	1	2	2	.6	.1	2	2						.7		5	4	11	5	6	14	6	2	2	7	13	.3	1	.3			2	.5
quinqueloba	2	2	3	2	1	4	13	9	35	14	42	8	12	25	6	5	9	17	11	4	5	4	4	1	2	2	.4	6	1		3	1				3	1	1	.5	.	5	6	5	8	.3	22	28	21	8	1	2	21	3	1	5	6	17
radians	2	2				1	4			.5				3			.5							.3				.5	1	.3		.4		.4	1	.	6	6																	
Globigerinella aequilateralis	2		3					.3									.						1	.	2	5		3	3	4	5	.4	4	.	4	3	1		3											1	.3	.			
Globigerinita glutinata	4	.	5		.5	4	.	11	20	10	10	.4	6	5	7	.	6	2	.3	1	1	1	1		1	1	4	.	2	2	5	.	1	1	1	6	13	4	2	8	5	.6	3	.7	17	23	14	6	8		.3	2	1		6	1	1
Globigerinoides conglobata																				3										.4										3	4																
rubra, etc	54	43	42	46	51	31	34	7	.3	.7	4	55	16	.3	18	22	27	38	19	60	48	43	55	48	20	24	24	41	58	50	25	30	58	.	57	32	32	19	39	28	6	7	9	.4	.5	2	9	22	3	11	23	.2	22	37	43	50	7
(typical G. rubra present)	x	x																			x		x									x	x				x	x	x	x																	
sacculifera	5	3	6																	3	.3													.4	2	3	.5		2	1	4																		
tenella	5	2	2	.4	1			2	1	1	4	3	5	.3	5	4	.0			5	1	3	5	2	7	6	8	3	2	5	8	7	9	6	5	14	11	9	7	10	7		1	.4		1	.7	2	2	.4	2	2	.0	4	5	1	
Globorotalia scitula	1	1	.	7	6	6	16	7	18	18	.4	3	9	4	10	.4	2		.7	3	6	11	4	1	.4	2	6	8	2	.4	9	7				8	.4	7	4	5	24	14	13	12	6	2	8	0	12	12	11	6	.3	9	1	3	13
truncatulinoides		6	1											.3		3							2	5	.4				.6												.4				.3			2	1	9	1	4		
Hastigerina pelagica																																	.4						1																
Orbulina universa			.3					2					4		8	6	3			2		2		1	1	1	6	.4	.3	4	.6	3	5	1	2	1	4	2		1			1		1		.7	4		2	3	8	2	4			7
BENTHONIC POPULATION (actual numbers)	23	53	14	61	46	41	35	47	83	140	84	53	103	38	38	74	26	83	196	111	164	132	111	23	218	48	91	16	68	86	96	5	43	56	62	51	1	15	2	65	189	80	121	127	291	59	159	87	301	243	95	351	13	58	92	33	29
Angulogerina angulosa				2	1					1		1	2		1				4	1	4	2		2	2			1			4		1		1	1						1		4				3		1				5		.
Articulina tubulosa & vars		5	2	1	3		1	4	11	4	4	9	3	1	27	7	4	37	25	14	7	11	4	14	63	29	51	7	3	2	12	1	3	1		1							1	3	10	6	1	6	146	38	8	9		5		3	4
Asterigerinata mamilla																			1	1	2	4	1	1			1		2		1		1		1					1	1	1							1		2		1		
Astrononion stelligerum															1								1																					1	6				2			1				
Biloculinella labiata		4																																											1	2											
Bolivina albatrossi			1																		1		1	8	1					5		1			2					1			2	5				3	3		7		2		1	
cf. ca															1										1					1						1																						
catanensis																																																					5			1		
difformis			1						1				1				1			2	3			2	2						3																						1	3				
dilatata dilatatissima													2		1				1		2	2			11	1										1		2											5	4	12	2		4				
pseudoplicata	4	1	2				.	2	6			4	3	3	2	1		2	5	3	6	7	10	10	11	1	1	6	3	2	3		2	1	4	1				2	2	2	3	3	7		2	1	1	2	6	7		4	1	2	
Bulimina costata		2				2			3	1	1				1			2	.		1		.		1				1						1						3	3	2	10	24	7	53	10	25			4			1		
exilis																												1																3			1	10						5		
gibba																									2																																
marginata																	.			1	1		1		2		1				1					1							1	1			2	2			7			1		
Cassidulina carinata	.		6	2	.				2	2		3	3	3	4			4	5	1	6		3	5	5		1	2								3							2	3	3	6			1		2				2		2	
crassa				2											2				4	4	4	3	1	4	11	1	1	1	1	2	3					3					1	1	1	1	.		1	4		1	3	11		.	1		
cf. oblonga			.		1	1																	3	3																					2						1	2	1			4					
cf. scabra				7	4	4	2	4	3	5	6			2	2	11	3	1	3	1	2	5	2				1																			5	11	2			2	1		1					2
subglobosa																							2	.		1				1														1						1	1					1	
Cassidulinoides tenuis																																													1				6								
Chilostomella mediterranensis															1		1							1	5	8		2				1				1	2				1			1						1			1	5				
Cibicides aff. floridanus			5		1	1	2		5	3	4			1	1	1																																	3		2									
kullenbergi																																																		12	16	40					
lobatulus	1			1					1					2		3		1		4		3		3	4	5	1			1	1	1	1	1	3	2			1		1	1	1					2				2	3			1	1	1
Eggerella bradyi, etc																																									2	1		2	9		2	2	6	60	8	17	1	7	4	5	1
Elphidium complanatum																			1						1				1								1				1														1		
pulvereum						1					1	.		1	4	1		1	3		2	.	2							2	2		2	1	4								2		2		3	2		3	1			.		1	
spp (see also below)	.		1	2																1	3	1		6	5	8		2		3	2	1			3	4										2	1	3	6	5	1		4	11			1	1	
Epistominella rugosa convexa																1		1	3	2		2	1	1	7		.	2			2	1																									
Gavelinopsis praegeri, etc	1	1				1					1			3						1	2			1				2	2				1	2	2				2	3	2	1	12	51	2					12					1
Globobulimina affinis																										1	16				1	5																					4				2				
pseudospinescens																																							2																		
? sp																																							1		1	7		1														
Glomospira charoides	2							1		1	7		1			1			2			3	1																																					
Gyroidina altiformis																																		4		1																							
delicata																									1																3	19		6	1	12				3									
cf. neosoldanii										1		1						1	5	2	8	3	6	7	4			10	10	8	1	4	7	3	6									2					3		1	1	1	2	1	1
umbonata																									1					1															1								1					
Hanzawaia rhodiensis	1			1																	2	2		3																				1														
Hoglundina elegans				-															1	1								1	3	16																							2					
Hyalinea balthica								1																1				2					8					2																1								
Loxostomum alatum																									2																									1					1			1		
Miliolidae		6	4	9	5	10	6	12	7	6	1	4	11	3	5	8	3	8	9	8	18	8	12	14	3	.		3	7	3	3		9	9	8			2	1	15	41	21	26	26	36	12	32	13	31	18	9	29		.	2		2
Miliolinella circularis		4	3	4	7	6	3	6	5	7	8	14	21	3	13	3	4	6	9	16	25	5	7	8	7	5		8	5	7	6		9	4	2					9	29	6	9	7	11	6	1	3		3	3	21		2	2		2
Neoconorbina terquemi	2		2	4					1			1	1					4	14	1	1	3	1	2	2			5	4	9			2	10	6	2					4	3	4			2			1	4	15		4	10	1	
williamsoni						1	1	1					1	2			.	2	1	8	4	5	2	5			1	3	4	3		1					2		1	2	2	1	4	1	1			2	3	2	17	1	3	3	1	
Nonion barleeanum, etc							1								3	1			1	2	.	2	1		1			1		1	5																				33		3			19		
sp. A		.			1					1			1	1	1			1	2	2		2	4	2	4	1	1				1				1					2				.	1		1	.		1	3	7		.	1		
sp. B					1		1			1	1			1	1				3		1	1	1		2			1	1											2		1	1									.			2		
Nonionella turgida									1												1				3																		1	1					.			2					
Patellina corrugata		2					1								1	2	.	1	1		.									1														1			4						3			.		1
Planorbulina mediterranensis	1																																				1																					
Pseudoeponides umbonatus var																																							3		9	16	5	6		2		3		1	4	1					
Pullenia quinqueloba				1								1		1	1				.	6	13	6	1	3				1											.	3				1	1	1	2		1		1			2	2	
cf. rivero																	1																							1		4	4	4	1										2	
Pyrgo anomala																																								2	17			1	3			2								
lucernula		5				1	2	4				1		1	4	6				3		3						1														5						1	2		1	1	4		1		3	6
murrhina	1	2		5	9		1		18	1	1			1																														10	6	6	1	28												
Pyrgoella sphaera		1											.			1	1	1			5		6															1						4	1	4	6	17	2	3	2		4					2		2
Quinqueloculina aff. lamarckiana		2	2	8	1	2	2		3	1	24	3	2								.	1							1														3							1				.	1		
Robertina translucens	2		1	1			1			1					1	3		1	2	1		1						2													1	1		1	1	1					3		4			2	2	2
Robulus spp																												1															1		1															
Rosalina aff. columbiensis				2	4	2	1	3	2		4		6	4	12	1	2	5	9	3	5	8	1	8	3			14	7	9	6		9	2	1	1				1		4	4	5	2	3	6	7			1	7					
globularis bradyi											1		2		1	1					4			2		1																																
obtusa											1			3					4	2	4		.		2			2			1		.		1							1				1						5		2		
spp				1		3	1	1	1	2	4	3	2	5	6	4			1	7	7	3	5	4				7		2			3	2	4	2	1		1	1		3	1	3	3	7	9		1	7	2	8					1
Rotamorphina ? involuta																		1	1		1		1											.																				1				
Sigmoilina distorta																								2																																		
tenuis															1										3					1																1	.		2								
Siphotextularia concava																				1			.	2			1																											3				
Spirillina vivipara					1		1							1			1	1									1	3	1											2		1		2	2			1	2	4		1		
Spiroloculina angulosa																1									1																										1					
canaliculata																1			1		1												1						1			1							1					1		
grata						1						2	3						4		3		2	2	3			1	1												1	1	1		1	2	1	3	2		3		4		2		
Spirophthalmidium acutimargo		1	1	.	2	4							3			1			3	1	1	2	1					2		1	1												1	1		1		2						3				
Uvigerina auberiana																									1				1	1	4														1							2			2		
mediterranea																									2																																
peregrina															2																															1	1										
Virgulina complanata																																																	8	9	1					
mexicana																									12		6			3					2				2		1	2						4					1	5		
Wiesnerella auriculata									1					3		1	2			7		1		2	3	2				1						1										1	3	1						13		2	2		
Miscellaneous spp	3	6	1	11	1	7	1	4	9	1	6	2	9	2	16	6	3	4	17	13	12	10	8	8	14	1	3	3	3	5	8	5	3	1	4	1		2		6	15	3	10	1	17	4	7	10	24	21	6	35	3	6	9	4	1
spp. listed elsewhere	1													1							2	1	1		4																		1		2	1	1							3				
Elphidium advena																												1																	1	1	1									2			2		

TABLE 13. Distribution of Foraminifera in selected samples from Core 192.

CORE 193

SAMPLE	1	2	3	4	7	8	10	11	14	15	17	18	20	21	22	23	24	25	26	28	29	30	32	33	34	35	36	37	39	40	41	42	43	44	45	46	47	48	49	51	54	55	56	57	58	59	60	62	63	64
DEPTH FROM TOP (CM)	1.5-2	5.5-6	9.5-10	19.5-20	49.5-50	59.5-60	79.5-80	89.5-90	119.5-120	129.5-130	149.5-150	159.5-160	179.5-180	189.5-190	199.5-200	209.5-210	221.5-222	229.5-230	239.5-240	259.5-260	269.5-270	279.5-280	301.5-302	309.5-310	319.5-320	329.5-330	339.5-340	349.5-350	369.5-370	379.5-380	389.5-390	399.5-400	409.5-410	419.5-420	429.5-430	439.5-440	449.5-450	459.5-460	469.5-470	489.5-490	519.5-520	529.5-530	541.5-542	549.5-550	559.5-560	569.5-570	579.5-580	599.5-600	611.5-612	621.5-622
PLANKTONIC POPULATION (%)	1900	2700	12000	9400	9300	9200	17000	52000	6800	7500	8100	9100	15000	3600	3700	1800	11000	22000	11000	17000	3000	7100	7900	19000	4200	15000	33000	11000	2500	4900	9700	25000	10000	4700	12000	20000	30000	32000	5500	2600	42000	54000	25000	36000	9000	7600	8000	4200	6300	13000
Globigerina bulloides	8	12	15	10	[illegible]	19	16	8	27	23	15	21	8	38	22	22	15	22	18	31	11	11	17	23	38	15	13	11	22	37	20	21	14	23	20	26	41	40	26	29	26	1	7	8	19	14	36	36	15	25
digitata	3	6		.5		1	1	5		2	4			4	3	1	1	6	1	3	3	2	2	3	6	4			1	4	1	3	1	1	3	3	1	1	6	1	.3		.5		4	1	1	1	1	2
eggeri	2	9	13	24	18	14	30	43	14	8	13	24	48	.3	2	4	18	29	7	2	2	2	4	33	2	33	53	20	1	.4	14	30	8	2	10	17	5	3	13	3	22	32	42	54	37	3	7	5	4	9
inflata	1	9	1		.3	1	2	1	12	12	21	8	4				16	7	15	18	7	19	11	4	1	8	1	5	5	1	23	22	12	1	15	10	1	2	9	3	11	37	9	8	11	.3	6	5	8	17
pachyderma		2	10	12	9	5	6	3	1	1	1	5	4	4			1	14	4	3	4	1	6	15		8	18	30	1	.4	14	7	7	.7	5	11	2	1	2	.6	2	3	6	8	3	1	4	5	2	1
quinqueloba	3	3	7	13	27	31	29	34	4	6	5	5	11	1	1	1	8	4	5	3	4	1	1	5	1	3	4	9	1	6	2	1		3	2	5	11	16	8	4	23	26	22	15	9	6	5	6	.3	2
radians	1	3																							.6	.3																					3			
Globigerinella aequilateralis	9	2				1			5	2	2	1	1	1	2	8	6		2	5	2	1	5	1	5	2		3	3	7		3	2	3	1	6	1	2		1					.4	2	4	1	2	
Globigerinita glutinata	1	9	14	7	9	9	4	4		1	4	4	6	6	2	12	2	3	3	2	1	2	6	7	3	4	2	3	2	4	5	1	3	19	6	9	7	5	11	13	2		5	4	6	29	14	11	6	5
Globigerinoides conglobata																									6				5					1														14	.5	1
rubra, etc	52	39	26	19	3	10	5	3	17	21	15	16	13	25	51	36	17	11	22	29	39	48	26	6	33	10	2	14	48	30	15	7	32	35	25	10	20	23	17	35	5		2	.4	9	35	14	6	34	21
(typical G rubra present)													x				x																	x		x	x									x				
sacculifera	5	6													6	3	4				.3		5	3	8	3				7	6	1	3		2		1				2					1	.4	.6	18	
tenella	11	3	1		.3	2			2	7	1	3	5	7	4	5	6	2	8	3	7	5	5	1	1	2	1	1	1	1	1	5	6	3	4	3	2	1	6	2	3				.4	6	2		3	7
Globorotalia scitula	.4	1	11	14	9	4	5	2	11	4	6	5	6	8			1	2	4	6	2	4	1	1	.6	4	3	5	2	1	3	1	4	2	2	5	3	1	6	3	1		6	1	3	.3	2	3	1	4
truncatulinoides		5				1			6	7	1	4		6			6	.6	6	.7	16	2	14	5	1	5	.4	1	6	1		3	17	.3																
Hastigerina pelagica	1										4				.7	1	3	3			1				.3				6	1																				
Orbulina universa	2	1	5		1	2	2	1	5	6	15	4	3	6	6	4	4	4	5	3	2	2	2	2	4	2	2	.3	6	4	1	4	1	6	7	3	5	5	6	6	2	.5		1	1	1	5	6	5	5
BENTHONIC POPULATION (actual numbers)	1	20	78	91	92	95	163	197	100	35	142	62	98	38	19	17	44	108	92	13	19	41	3	446	7	45	344	116	10	25	12	55	25	26	43	60	70	36	61	9	86	190	187	396	9	8	53	58	32	51
Articulina tubulosa 8 vars				2			58	26	18		20	4	20	9	5	9	6	13	10	7		5		9		2	11	3		1		4			2	9	4	10	22	3	14	44	58	129	3	2	15			3
Bolivina albatrossi						1		3				3	1																																					
pseudoplicata									3		1								1					2	1	1	3	3				1				1		1	1				2						2	
Bulimina aculeata																				2			1	278		4	13																							
costata			2		27	38	26	17				5						3			1			27		7	49	4							1							1	4	11						
exilis						3	24					2																																						
Cassidulina carinata		1	2	1		1																					2																					3		
cf sicula			3	1		1	1	1																				3							1													1		
Cassidulinoides tenuis							11	65				1																															2							
Chilostomella mediterranensis							1	3			4	15	1				1	3	1					2		1	4									1					1	31	9	7						
Cibicides aff. floridanus		5	16	26	1	2																														5	1	1	2											
kullenbergi	1						1	4	39	25	42	3						27	41					4				68																						
lobatulus			2														1							1																										1
wuellerstorfi		2																									1																							
Eggerella bradyi, etc							1	10	19	2	44	12	19	9	2	1	16	2			5	16																				1	7	16		3	10	13	10	18
Elphidium pulvereum									1																																	1						1		
Gavelinopsis praegeri, etc.					7			1			1	1															1																							
Globobulimina affinis						1				2		8	49	1				4	1					8		1	22	1					2		3						3	11	4	9	3				1	
? sp		1			1		4	32					1																												1	3								
Gyroidina delicata								3																4			4												1		7	3	41	141	1					
cf. neosoldanii									2	1	2						6	1	1			3	1	6	5		6		1	7	3	5	8	16	20	1	14	2	1	1	45			3			8	9	3	7
Höglundina elegans		2	1	1										1																																				
Miliolidae			6	7	13	12	6	3	1		2	1		1	2	2	1		5	1		1		3							5	2	2				2	1				1	2	2				2		
Miliolinella circularis			19	28	10	.3	2					1							1		1																							1						
Neoconorbina williamsoni					1	1			1		1								1								1												2	1		2								
Nonion barleeanum, etc.	-																1	1	7		3	7							1				2			1														
Nonionella turgida																								2			3									1														
Pseudoeponides umbonatus var.			1		3	5	8	19	1												2	3	1	10		5	33	14	5	5		2			1	19	30	10	22		1	13	3	11			2	12	10	5
Pullenia bulloides																											1	1	1			2	2		3	7	1	1	2				6	1		1	3	2		
quinqueloba										1	1			1							1																													
cf riveroi					1									2	1			2	1								2	7								1	1	2	1											
Pyrgo anomala			1	1																																						1		1						
lucernula		1	5	3		2	5	5	5	4	5	2	1	8	5	1		2	3					1			1	4		7	1	30	3	5	7			2												
murrhina			1	2	1			1										1						24			46														2	14	1							
serrata																						1		31		19	94																							
Pyrgoella sphaera		2			7	2								1					3																															
Quinqueloculina aff. lamarckiana		2	6	10																				2																								5		
Robertina translucens					1						9	1		4	2	2	4	5	5																								1	1						
Robulus spp.									1																1	2	2									1						1	3	1						
Rosalina aff. columbiensis					1																2																										2		1	
Sigmoilina schlumbergeri																											2											3	2											
tenuis																																															2			
Spiroloculina canaliculata			2						1				1															1				1	2	2			1	2			1					1	2		1	6
Spirophthalmidium acutimargo			4	2											2									2																										
Virgulina complanata									1													1														2	2				2	27	24	15	1		3			
mexicana																								3			1										8					6	.4	29						
Miscellaneous spp.		3	7	7	18	11	14	3	7		7	3	5	1		2	7	44	10	3	3	4		27		3	40	6	2	3	2	8	4	3	4	10	6	1	5	2	9	29	6	15	1	1	5	9	4	10
spp listed elsewhere		1				2	1	1			3						1		1		1						3	1		2	1				1	1				2		1		2			1	1		1

TABLE 14. Distribution of Foraminifera in selected samples from Core 193.

CORE 194

SAMPLE	1	2	3	4	7	8	13	16	17	21	23	24	25	27	28	31	33	35	36	37	39	40
DEPTH FROM TOP (CM)	2-25	9.5-10	19.5-20	29.5-30	59.5-60	69.5-70	119.5-120	149.5-150	159.5-160	199.5-200	219.5-220	229.5-230	239.5-240	259.5-260	269.5-270	299.5-300	311-315	329.5-330	339.5-340	349.5-350	369.5-370	379.5-380
PLANKTONIC POPULATION (%)	1600	3200	2000	2600	6300	5200	8400	3200	6000	9400	500	3800	1600	1900	4700	9100	3100	690	6500	3400	4600	6100
Globigerina bulloides	14	13	12	14	16	14	20	9	14	29	19	20	51	30	30	27	22	8	12	18	27	22
digitata		1								2		2						3	1	5	1	1
eggeri	14			6	3	6	2		15	2		4		2	2	23	34	24	36	6	7	
inflata	3	1		6	3				3	1	14	5	22		1	4	1	1	1	10	3	6
pachyderma	6				9	8	8	2	6	3		4			5	8	14	2	6	2		5
quinqueloba	.1	2	1	3	3	8	11	24		26	18	3	3	31	24	5	3	5	2	3	2	2
radians			4	3				.5	1								3				3	1
Globigerinella aequilateralis	4		4	3													3	6		4	4	6
Globigerinita glutinata	15	12	5	17	1	17	5	15	14	10	4		5	2	3		2		5		2	2
Globigerinoides conglobata															5							
rubra, etc	19	34	61	54	30	18	9	3	13	5	9	20	20	28	24	.2	15	9	16	36	40	39
(typical G. rubra present)	x	x	x	x															x	x		x
sacculifera	1	20		2																		
tenella	3	4	3	3	3			4	6	3				4				11	4	4	1	6
Globorotalia scitula	5				4	19	6		2	8	4	4	1	4	7	1		.34	5	3	1	2
truncatulinoides	1			1				3								7		3		10		1
Hastigerina pelagica		5																				
Orbulina universa	2	4	6	6					3	2		1				1	5	6	6	3	2	2
BENTHONIC POPULATION (actual numbers)	22	0	2	2	60	125	81	[illegible]	[illegible]	[illegible]	[illegible]	89	1	46	93	100	215	103	1	1	1	26
Angulogerina angulosa	1							2		1	4				3		7	1				
Articulina tubulosa & vars					10	7	24	16	22	24	7	.8		.3	17	35	4	4		5	1	6
Asterigerinata mamilla							2	1				2					1					
Astrononion stelligerum																						
Bolivina albatrossi	1							3									.8					
attica																						
catanensis																4	3	4				
difformis						2				2	1				1	2	3	2				
dilitatus dilitatissima															1		20					
pseudoplicata			1		3	3	3	5	6	8	4	2			4	1	2	3	1			5
Bulimina aculeata																1		1				
costata								2								2	14					
exilis																						
gibba																1	5					
marginata																1	3					
Cassidulina carinata	1				2	0	1	4	3	2		5	2	2	3	1	23	1				
crassa										2					1	4	1					
cf. oblonga										1						1	3	1				
cf. sicula			1					11	2	7	1	2				2	20			1		
subglobosa							1	4		1							15	2				
Cassidulinoides tenuis																						
Chilostomella mediterranensis								3		1						1	1	10				
Cibicides aff. floridanus								1														
lobatulus	1							3		3	3			1	6	2	4					
Eggerella bradyi, etc.																						
Elphidium advena																						
granosum					1																	
pulvereum						1		3	2	3	4						6				1	
verriculatum																						
spp	2							0	2	4	5				1			3				
Epistominella rugosa convexa																3	.2					
Gavelinopsis praegeri, etc	1							2		2	3	1					6	1				
Globobulimina affinis																	1					
? sp																						
Gyroidina delicata																						
cf. neosoldanii	1							1				1				7	2			1		
umbonata																1						
Hanzawaia rhodiensis															1		8			1		
Hoglundina elegans																						
Hyalinea balthica																1	10					
Lagenonodosaria scalaris																	2	2				
Loxostomum alatum																1	1					
Miliolidae	2		1		4	5	4	24	6	15	17	3		2	4		4	9	2			3
Miliolinella circularis	4			2	6	23	13	24	.9	33	34	26	3	16	17	2	4	5		5		
Neoconorbina terquemi	1				2	4	2	1	2		6			4		1				1		5
williamsoni						1		1		4				1	1		4					1
Nonion barleeanum, etc																	3					
sp. A						1		4		2	3					1		1				
sp. B																	3					
Nonionella turgida											2			1	1							
Patellina corrugata						2																
Pseudoeponides umbonatus var																						
Pullenia quinqueloba																	2					
cf. riveroi											5	1										
Pyrgo anomala																						
lucernula	1						1		2			2			2							
murrhina					11	4	3	2	3													
Pyrgoella sphaera																						
Quinqueloculina aff. lamarckiana	1				5	4	12		6													
Robertina translucens						2	1											1				
Robulus spp																1	2					
Rosalina aff. columbiensis						7	2	.2	6	5	11	10		1	9	1	1	1		1		3
globularis bradyi					1	1																
obtusa								1	3	3	2						5	2				
spp						5	3	6	1	5	13	4		1	3		6					1
Sigmoilina tenuis															1			2				
Sphaeroidina bulloides																	1					
Spirillina vivipara					1	2		2														
Spiroloculina canaliculata							1															
grata						2		7			3	1		1	1							
Spirophthalmidium acutimargo	1							3			1							2				
Streblus beccarii & vars																						
Uvigerina auberiana																	3				1	
peregrina								1														
Valvulineria complanata																						
Virgulina complanata																						
mexicana								6								3		40				
Wiesnerella auriculata						3	1	6		6	8			1				2				
Miscellaneous spp	3				3	7	8	35	5	6	20	7			12	5	20	4			3	2
spp. listed elsewhere							1					1	1	1		2	2					

SAMPLE	43	44	45	46	47	48	51	52	53	55	56	57	58	59	62	64	65	66	68	69	7	73	74	75	76	77
DEPTH FROM TOP (CM)	409.5-410	419.5-420	424-424.5	429.5-430	439.5-440	449.5-450	479.5-480	489.5-490	491-495	519.5-520	529.5-530	539.5-540	549.5-550	559.5-560	589.5-590	610-610.5	619.5-620	629.5-630	649.5-650	659.5-660	679.5-680	689.5-690	692.7-693.2	699.5-700	709.5-710	718-718.5
PLANKTONIC POPULATION (%)	10000	8500	21000	4000	2300	2200	3300	5200	39000	9000	25000	4000	6600	900	22000	16000	6100	9500	11000	21000	24000	1900	27000	3800	2500	4300
Globigerina bulloides	11	36	8	20	28	29	7	8	9	20	22	18	28	36	32	27	22	0	21	18	3	16	8	35	25	20
digitata				4	5	4	2	3						4				1	1		3			4	6	4
eggeri	23	22		9	3	4	16	30	31	21	11	12	22	16	28	24	21	17	12	62	30	43	27	2		2
inflata	1	0		11							2	8		6	3	1			9		2		2	2	1	17
pachyderma	3	5	3						4	1	7	8	6		6		13	13	2	1	15	2	2			
quinqueloba	6	5	15	2	7		4	1	7		10	4	4	5	9	.5	.6	27	13	15	8	23	3	3	3	4
radians		4	1		7		7	1		4	5															
Globigerinella aequilateralis	3			3	2	8	4	4	5	2	2	3							2				1		4	7
Globigerinita glutinata	5	1		1	3	4	14	1	5	2	8	6	6	1	1	1	1	12	9			5	3	1	9	8
Globigerinoides conglobata				2								2	4													
rubra, etc	16	2	2	26	53	53	14	24	23	21	18	23	.5	5	2	3	.3	.7	15		5	4	32	30	42	23
(typical G. rubra present)			x			x	x	x	x	x	x											x	x			x
sacculifera					7				7		3	1		4									3		3	4
tenella	8	4		2	4	9	17	12	1	11	4	6	9		3	4	.3		3		.3	2	1	4	1	2
Globorotalia scitula	15	8	20	5			14	6	4	7	6	5	10	20	4	8	16	1	8	2	6	2		5		5
truncatulinoides																						1	6	8		
Hastigerina pelagica					3	4																				
Orbulina universa	2		2	7	5	3	1	2	6	5	9	4			.6	.6	.3	8	5	2	2	1	12	6	6	4
BENTHONIC POPULATION (actual numbers)	36	11	13	1	22	11	24	230	103	4	721	56	94	81	908	435	98	113	134	4	32	24	169	56	19	3
Angulogerina angulosa							4	7			5				7	10			2			1	2	1		
Articulina tubulosa & vars	5	1			5	3	5		1		1	4	2	3	8		6	9	40		3	2		17	5	1
Asterigerinata mamilla															3	3	1	1	1							
Astrononion stelligerum								1	1						6		2		2							
Bolivina albatrossi	3							6	8		83				87	19						1	6			
attica								3	1		1				1											
catanensis	1						5	32	1	1						2		1		1			7			
difformis							2	2			4							2								
dilitatus dilitatissima	2	1					4	7	5		17			1	23	23	1	6	2			6	2			
pseudoplicata		2	1		2		7	10	1		16	1	3	5	20	15	7	6	3	2	1		1	2	2	
Bulimina aculeata															1											
costata							1	5	5		0		1	2	33	4	1		1				10			
exilis											1				6							1				
gibba									2							8		1					2			
marginata							1	18	3		1				3	9		1					5			
Cassidulina carinata		1	1				4	13	5			1	1		20	8	1	2				1	2			
crassa		1					4	10	7		11			1	6	9		8	1				8	1		
cf. oblonga							1	3	3		18		1		8	7	1	2				1				
cf. sicula									3		33				28	6					1				1	
subglobosa								1	2														3			
Cassidulinoides tenuis											1					2										
Chilostomella mediterranensis	3	2					4		1			1			1	2						2	7			2
Cibicides aff. floridanus															2											
lobatulus							2								8	28	1							1	1	
Eggerella bradyi, etc.											5				9	3					5	1	1	2		
Elphidium advena						1		1	1		1				1											
granosum											3															
pulvereum	2		1			1		7	6		9				10	21		3	1						1	
verriculatum											2				3											
spp	1				1		9	10	4	1	20	2	3	3	23	15	1	10	1			1			1	
Epistominella rugosa convexa	1																									
Gavelinopsis praegeri, etc						1	6	20	.3		86			1	89	22	5	1	1				1			
Globobulimina affinis		4						2							1	2							18			
? sp											1	4		1												
Gyroidina delicata									1		14		1		.1	2		1								
cf. neosoldanii	1				1	1	1		2						6		1				1		1			
umbonata	1				1											4	1									
Hanzawaia rhodiensis																		1					6			
Hoglundina elegans							1	1			2				5								8			
Hyalinea balthica							3	6																		
Lagenonodosaria scalaris							1												1							
Loxostomum alatum	2															4							9			
Miliolidae					1	3		1			128	11	23	23	178	88	19	46	18		7		4	1	2	
Miliolinella circularis					1	6					45	9	17	6	45	7	9	15	11		5		5	8	1	
Neoconorbina terquemi					1			1	1		25		1	3	4	12	1	3	5				1	1	1	
williamsoni							3	1	3		11		2	2	12	2		5		1		1	2	1		
Nonion barleeanum, etc							2	1	1		1				1	4	1					1	6			
sp. A							4	1			5		1	1	5		3	3	1							
sp. B	1						3		1		6				7	1	2									
Nonionella turgida	1	1					1				1															
Patellina corrugata											2				3		2									
Pseudoeponides umbonatus var											18	9	12	2	25	5		2	3		1					
Pullenia quinqueloba							1				3				3	2		2								
cf. riveroi									1		2		1	3		2	4	4								
Pyrgo anomala											2				4				2							
lucernula															1						3			2		
murrhina												4	2	4												
Pyrgoella sphaera													5	4	3		6	6	8							
Quinqueloculina aff. lamarckiana																							1			
Robertina translucens											2				5									2		
Robulus spp								1					1													
Rosalina aff. columbiensis					5	1	3				25			2	26	1		1	3							
globularis bradyi											3				2											
obtusa					1		2	3			6		1		2	3		2	2							
spp					1		3	4	4		44	1	3	5	26	21	2	6	2						3	
Sigmoilina tenuis							2																			
Sphaeroidina bulloides																							7			
Spirillina vivipara							1								2											
Spiroloculina canaliculata							1								3									3		
grata											6				3	2	1	2	1				1			
Spirophthalmidium acutimargo													1	2			1	1								
Streblus beccarii & vars															2	1		1								
Uvigerina auberiana															1	2										
peregrina									1		7				6								6			
Valvulineria complanata								1	1						1	1										
Virgulina complanata							1								1						1					
mexicana	9		6	1			8	3								2			2							
Wiesnerella auriculata											6			1	17	1	4	1								
Miscellaneous spp	3	3	4		2		24	41	11	2	30	9	11	5	53	44	13	17	17		4	4	36	8		
spp. listed elsewhere								1	1		4				1			1								

TABLE 15. Distribution of Foraminifera in selected samples from Core 194.

CORE 195																							
SAMPLE	1	2	5	9	11	12	14	15	20	21	23	24	25	26	27	28	29	31	34	35	36	37	40
DEPTH FROM TOP (CM)	1.-5	9.5-10	39.5-40	79.5-80	99.5-100	109.5-110	129.5-130	139.5-140	189.5-190	199.5-200	219.5-220	229.5-230	240-240.5	249.5-250	259.5-260	269.5-270	279.5-280	299.5-300	329.5-330	340.5-341	349.5-350	359.5-360	389.5-390
PLANKTONIC POPULATION (%)	2300	[illegible]	5400	[illegible]	6200	[illegible]	18000	1600	4500	8800	5600	7700	2500	2400	[illegible]	[illegible]	5600	4600	15000	31000	2200	2500	2200
Globigerina bulloides	25	6	12	8	12	18	18	14	30	38	8	17	26	43	17	14	32	22	8	13	2	25	29
digitata	.3							2					3	3		1					2	3	5
eggeri	8	23	0	12	.5	4	7	3	.4		.3	4	1	2	26	47	2		42	70	2		1
inflata	6						6	24	20	1	2	15	3	2	9		13	4	4	1	9		.4
pachyderma	7	20	0	12		2	3					7	3	2	6	8			4	2			
quinqueloba		4	2	22	3	9	10	4	6	4	8	1	2	2	1	2	6	.	3	8	.4	.3	1
radians	9		.					1		.4								.3				.3	.5
Globigerinella aequilateralis					4								8	3	5	.		4	3		2	1	5
Globigerinita glutinata	10	3	2		[illegible]	5	20	2	4	1	1	1			7		2	2	4	1	1	2	1
Globigerinoides conglobata	.3											1									4		
rubra, etc	29	23	.9	22	.7	1	2	26	30	30	77	24	52	39	16	.4	41	60	23	1	49	57	54
(typical G. rubra present)	x																		x				
sacculifera																						4	1
tenella	6	6	2		4	.6		5					4	1	7	.		4	4		6	3	3
Globorotalia scitula		3	6	4	13	29	22	3	3	3	2	9	6	2	5	6	3	3	4	2	2		
truncatulinoides	1		.3															1					
Hastigerina pelagica																						.6	
Orbulina universa					4			8		.4			5	1	.	6	.6	.3	.4	2	5	3	3
BENTHONIC POPULATION (actual numbers)	19	77	22	48	52	28	105	48	44	55	52	69	2	12	107	4	9	17	1	2	1	2	1
Angulogerina angulosa																1							
Articulina tubulosa & vars	2	7		12	13	12	31	3	18	6	10	49		2	106		7	5			1	1	
Asterigerinata mamilla	1						1		1		1	1											
Astrononion stelligerum																							
Bolivina difformis								1						1									
dilitata dilitatissima							1																
pseudoplicata					1	2				3		1				1	1	1	1				
Bulimina exilis																							
Cassidulina carinata					2					1		1		1									
crassa																1				1			
cf. oblonga							1			2				1									
cf. scula									2														
Cassidulinoides tenuis																							
Chilostomella mediterranensis																							1
Cibicides lobatulus						1		1		1	1							1					
Elphidium pulvereum									1			1		1									
spp							1	1		2	2												
Gavelinopsis praegeri, etc				1						1								1					
Globobulimina ? sp																							
Gyroidina delicata																							
Miliolidae	1	26	3	8	4	4	8	2	2	5	6	1			1			4					
Miliolinella circularis	7	18	4	5	6	3	38	29	2	20	17	2						2					
Neoconorbina terquemi		3	2		4		1	3	1		2	2	1	2									
williamsoni	1					3				2								1					
Nonion sp. A		1	1	2				1						1									
sp B										1													
Patellina corrugata																							
Pullenia cf. riveroi																							
Pyrgo murrhina		8	2																				
Pyrgoella sphaera																							
Quinqueloculina aff. lamarckiana				5																			
Robertina translucens		1							1		1												
Rosalina aff. columbiensis		1				1	4	3	2	1	10			1				1				1	
globularis bradyi																							
spp.						1			2	5	1	4					1						
Rotamorphina ? involuta																							
Spiroloculina grata									1	1													
Virgulina mexicana														1		1							
Wiesnerella auriculata						1	6			1		2											
Miscellaneous spp	1	1		3	1		2	4	1	2		3	1							1			
spp listed elsewhere							1					1											
Spirophthalmidium acutimargo					1													1					

CORE 195																		
SAMPLE	43	44	45	46	47	48	49	5	53	54	55	57	59	60	61	62	63	66
DEPTH FROM TOP (CM)	419.5-420	429.5-430	438-438.5	449.5-450	459.5-460	468.5-469	479.5-480	499.5-500	519.5-520	529.5-530	539.5-540	559.5-560	579.5-580	589.5-590	599.5-600	609.5-610	618.5-619	649.5-650
PLANKTONIC POPULATION (%)	7800	1100	6200	6600	7800	1100	5100	9200	6300	9400	6700	8800	3100	2600	3800	14000	20000	5800
Globigerina bulloides	16	9	17	26	28	33	23	27	9	45	26	14	63	11	16	10	1	17
digitata						4									1			
eggeri	29	2	19	23	22	2	16	14	39	13	17	32	3	4	9	44	58	69
inflata		16			1	2	8	15							9	7		6
pachyderma	1		12	16	23	3	5	.4	22	7	13	12		7	2	10	5	
quinqueloba		6	9	6	12	10	4	9	19	17	14	22	2	54	18	10	22	11
radians	1					2	3	1										
Globigerinella aequilateralis													.5					
Globigerinita glutinata		4	5		1	.	9	12	6	15	15	5	28	1	6	8		.3
Globigerinoides conglobata			7			.4												
rubra, etc	35	38	1		2	5	7		.3	.3			1		27	1		.3
(typical G. rubra present)	x					x												
sacculifera																		
tenella	10	2	12		1	.4	1					1	1		1			
Globorotalia scitula	4	12	18	28	9	20	14	5	1	2	15	9	1	13	5	9	10	
truncatulinoides															.4			
Hastigerina pelagica																		
Orbulina universa	4				4			3	2			5			5		4	1
BENTHONIC POPULATION (actual numbers)	1	34	49	20	44	26	34	18	31	24	35	36	15	43	43	165	12	2
Angulogerina angulosa															1			
Articulina tubulosa & vars					3	1						1		1	2	114		
Asterigerinata mamilla			1		2													
Astrononion stelligerum																		
Bolivina difformis															2			
dilitata dilitatissima												1				1	3	
pseudoplicata				1	2		3				1	3			1			
Bulimina exilis															1	4		
Cassidulina carinata						1				1		1						
crassa													1				6	
cf. oblonga							1					1				1		
cf. scula																		
Cassidulinoides tenuis															1	23		1
Chilostomella mediterranensis						1												
Cibicides lobatulus			1					2		1					1			
Elphidium pulvereum												1				1	1	
spp										1								
Gavelinopsis praegeri, etc					2										2			
Globobulimina ? sp						2										4		
Gyroidina delicata									2							9		
Miliolidae		3	13	7	15	8	3	9	15	6	26	22	8	14	7	6		
Miliolinella circularis		11	9	4	4		2	1					1	10				
Neoconorbina terquemi				1						1				1	4			
williamsoni			1		1		1			1				2	5			
Nonion sp. A											1	1	2					
sp B					2						1							
Patellina corrugata				1		1				1		1						1
Pullenia cf. riveroi				1	1	1				2		1						
Pyrgo murrhina		1	6															
Pyrgoella sphaera					2		1	3	2					11	2			
Quinqueloculina aff. lamarckiana		15	13	1	8		2											
Robertina translucens																		
Rosalina aff. columbiensis			2	2			2		5				2		3			
globularis bradyi											1							
spp.						1	1		3		1							
Rotamorphina ? involuta															2			
Spiroloculina grata							1							1				
Virgulina mexicana						2									1			
Wiesnerella auriculata							1											
Miscellaneous spp	1	3	3	2	2	8	6	3	3		4	3	1	3	7	2	2	
spp listed elsewhere		1							1						1			
Spirophthalmidium acutimargo																		

CORE 195																								
SAMPLE	67	68	69	70	71	73	74	75	76	77	78	79	81	82	83	84	86	87	88	89	90	91	92	94
DEPTH FROM TOP (CM)	659.5-660	669.5-670	679.5-680	689.5-690	699.5-700	719.5-720	729.5-730	739.5-740	749.5-750	759.5-760	769.5-770	779.5-780	799.5-800	809.5-810	819.5-820	829.5-830	849.5-850	860-860.5	869.5-870	879.5-880	889.5-890	899.5-900	909.5-910	929.5-930
PLANKTONIC POPULATION (%)	27000	12000	2800	2100	9000	8500	3300	2500	2000	5400	29000	25000	34000	10000	5500	5300	3300	29000	2900	4200	4200	4300	7200	4700
Globigerina bulloides	25	28	29	26	16	9	33	27	37	8	23	14	5	33	23	21	13	13	43	18	40	29	30	20
digitata				6	2		.	4	3	5					.6	3	2			1			2	
eggeri	27	23	14	5	36	38	7			3	16	63	60	27	17	15	7	16	8	10	3	2	2	13
inflata			4	8	12	13	4	3			13	18			12	15	20	4	3	21	15	24	10	8
pachyderma	.7	20	.	4	2		1				1	4	.6	28	2	1		1	4	6	1	1	1	19
quinqueloba	10	3	9	.4	3	4	3	2	.4	1	1	16	33	3	9	4		7	5	5	23	5	12	3
radians					.5					.6					.3			.4	1	4			1	
Globigerinella aequilateralis				1	2			2	6	7	1				1	.3	3	4		1			2	
Globigerinita glutinata	6	.3	.3	9	2	6	1	9	8	6	.7			2	3	.6	3	8	2	5	11	9	13	1
Globigerinoides conglobata																								
rubra, etc	1	10	16	20	14	25	21	47	31	27	15	1			20	26	34	32	31	30	1	13	8	18
(typical G. rubra present)						x			x	x	x	x			x		x	x						
sacculifera						.		2	3	1	2													
tenella		.3	.3		2	5	4	6	6	10	3	1			7	1	3	10		.4		.4	3	
Globorotalia scitula	11	9	13	7	1	1	25			2				3	.6	.6	1	4	5	2	6	9	13	15
truncatulinoides			5		6	6					16					9	10							
Hastigerina pelagica										.6														
Orbulina universa	3	2	3	22	2	1	3	.7	5	5	3	.3	1	4	4	3	3	4				7	3	2
BENTHONIC POPULATION (actual numbers)	7	16	7	9	7	0	42	5	4	5	9	14	14	87	21	24	29	0	87	61	5	69	60	23
Angulogerina angulosa																								
Articulina tubulosa & vars	2	6		3	2		8	2	3	1	6			66	8	3	24		37	41	2	26	28	15
Asterigerinata mamilla													1	1		1								
Astrononion stelligerum													1	3										
Bolivina difformis					1										1					1				
dilitata dilitatissima	1													2										
pseudoplicata											1			3	3				1		1	1	1	
Bulimina exilis																								
Cassidulina carinata																								1
crassa					1		2					6	3	1										
cf. oblonga												1	1						1					
cf. scula																								
Cassidulinoides tenuis																								
Chilostomella mediterranensis		1												1										
Cibicides lobatulus	1						2						1	1									1	
Elphidium pulvereum												2	2			2			1			2		
spp							1					2	1			1			2				1	
Gavelinopsis praegeri, etc				1			1																	
Globobulimina ? sp																								
Gyroidina delicata																								
Miliolidae	1	4	3	1	1		12	1			2				4	6			6			13	11	1
Miliolinella circularis		1					7	1											19	9		5	1	
Neoconorbina terquemi			1							1						1			3			3	6	1
williamsoni			1											1					1			1		
Nonion sp. A				1			1								1								1	
sp B	1	1														1						1		
Patellina corrugata																								
Pullenia cf. riveroi																			3	4	1	1		1
Pyrgo murrhina																			1	1	1	1		
Pyrgoella sphaera																								
Quinqueloculina aff. lamarckiana																								
Robertina translucens				1				1		1				5	2	7	3		1	1		5	2	
Rosalina aff. columbiensis	1	2													1							3	1	1
globularis bradyi																			1			1		
spp.																			2				1	
Rotamorphina ? involuta																								
Spiroloculina grata		1																	1			1		
Virgulina mexicana																								
Wiesnerella auriculata			1				2												1				2	3
Miscellaneous spp				2	1		5		1	2		3	4	3		2	1		6	4		5	3	
spp listed elsewhere			1		1		1								1									
Spirophthalmidium acutimargo																							1	

TABLE 16. Distribution of Foraminifera in selected samples from Core 195.

CORE 196

SAMPLE	1	2	4	7	8	13	14	17	18	22	26	31	34	36	39	40	41	42	43	44	45	47	48	49	51	52	53	55	56	58	59	60	62	64	67
DEPTH FROM TOP (CM.)	1-1.5	9.5-10	29.5-30	59.5-60	69.5-70	119.5-120	129.5-130	159.5-160	169.5-170	209.5-210	249-249.5	301-301.5	329.5-330	349.5-350	379.5-380	390.5-391	399.5-400	409.5-410	419.5-420	430-430.5	438-438.5	459.5-460	469.5-470	479.5-480	499-499.5	501.5-502	509.5-510	529.5-530	539.5-540	560.5-561	569.5-570	579.5-580	599.5-600	619.5-620	649.5-650
PLANKTONIC POPULATION (%)	80	4500	7900	7600	9600	5300	8500	5700	4800	12000	8100	11000	6000	3000	3900	17000	2500	3300	4200	260	8600	3500	7900	4900	27000	23000	5800	2900	6800	11000	6100	4700	8900	20000	230
Globigerina bulloides	13	9	10	9	10	20	9	12	29	46	22	20	20	20	8	20	20	20	15	14	37	29	23	22	26	13	37	17	12	25	28	15	29	11	13
digitata	1				.3	.3		6			1	2	2	5	1		4	2	2	1		2	1	3	.5		3	3	1	.3		.3		.3	
eggeri	23	13	18	14	25	9	7	11	1	5	20	22	13	1	55	61	2	1		43	27		6	.3	15	67	1		1	16	12	13	23	14	26
inflata	2	18		2		1	13	17	20	11	9	7	3		.4		1			1	.4		10	15	13		4			8	6	2	3		5
pachyderma	8	8	13	11	12	2		2		3	6	5		1	2					3	1		1		6	1	.5	.3		13	15	3	21	12	8
quinqueloba	8	.5	9	4	14	34	5	6	36	12	5	2	2	3	3	7	.6	.5	1	1	5		3	1	6	7	3	1		8	6	25	9	43	33
radians		.7										.3									3					.6		.3				3	.4		
Globigerinella aequilateralis											1	2	6	11	5			3	2	3	10	2		3			2	1	10	.3					
Globigerinita glutinata	6	10	13	10	11	12	21	6	2	2	1	6	2	2	2	1	2	.7	2	3	.7	2	2	.3	3		.5	1	3	3	1	17	10	6	4
Globigerinoides conglobata																														1					
rubra, etc.	35	33	21	41	13	5	20	22	4	12	13	26	35	44	15	2	65	67	67	26	4	55	48	40	23	4	40	66	65	8	10	2	1		4
(typical G. rubra present)												x	x	x	x	x		x	x			x				x			x						
sacculifera	1																		3			3						1	2						
tenella		.7	1			9	.4	13	.3		3	2	10	4	1	3		4	5	.4	2	6	2	8	2	1	2	7	2	1	.3	1	.4		
Globorotalia scitula	2		15	9	14	7	24	1	7	9	3	2	3	2	5	3	1			1	5		2	3	5	2	2			16	21	18	1	12	7
truncatulinoides	1	5									15	1											1												
Hastigerina pelagica												.3	.3						.4			.5					.3	.6							
Orbulina universa		2						4			.4	2	3	7	2	2	4	1	2	3	4	.5	1	4		4	4	1	4				2	1	
BENTHONIC POPULATION (actual numbers)	0	18	166	108	44	42	26	14	28	58	58	30	10	7	0	1	2	5	0	1	1	4	59	22	132	1	2	1	1	19	16	149	51	17	0
Articulina tubulosa & vars.		4	85	65	12	12	4		4	32	53	13	6	4								1	51	13	114		1			5			1	4	
Bolivina catanensis																								1	2				1			4			
difformis						1					1	1											1		2						1	3			
dilitatus dilitatissimus																					1				1							8			
pseudoplicata						1			1	2													1							3		10	1		
Bulimina costata																																3			
exilis																																4			
marginata																																3			
Cassidulina carinata																																11			
crassa				1								1				1									4							1	1		
cf. sicula											1																					2			
Cassidulinoides tenuis																																2			
Chilostomella mediterranensis														1																		3			
Cibicides lobatulus												1					1										1					2	2		
Elphidium crispum				1																												2	1	1	
cf. minimum																																2		1	
spp.				2			1					1																				2		1	
Gavelinopsis praegeri, etc.																																5			
Loxostomum alatum																																2			
Miliolidae		3	2	2	3	6	2	1	3	2								1				1	2	1						4	6	25	22		
Miliolinella circularis		8	71	29	18	11	12	11	9	3		2												1						1	3	8	7		
Neoconorbina terquemi			1		1				1			1	1					1																	
williamsoni			1		1	3		1	2			1												1				1			1	4	1		
Nonion sp. A				1					2	2								1						2						2	1	1	1	3	
sp. B				1									1																		1	2			
Patellina corrugata					1					1																						3		2	
Robertina translucens					1				2	2																									
Rosalina aff. columbiensis					1	2	2			4		1	1					1				1		1						1	1	1	1	1	
obtusa				1						2															2										
spp.		2		1	2	3											1															6			
Spirillina vivipara				1																			1									1			
Spiroloculina grata							3		1									1																	
Wiesnerella auriculata					1	2			2	2				1									1									1	3		
Miscellaneous spp		1	5	1	2	1	2	1	1	4	2	8		1								1	1		6	1				3	2	22	9	3	
spp. listed elsewhere				2	1					2			1							1			1	2	1							6		1	
Virgulina mexicana			1								1																						1		

TABLE 17. Distribution of Foraminifera in selected samples from Core 196.

CORE 197

SAMPLE	1	2	7	8	10	11	15	16	17	19	20	22	24	25	26	27	28	29	30	31	33	34	36	38	41	42	43
DISTANCE FROM TOP (CM)	2.5-3	9.5-10	59.5-60	69.5-70	89.5-91	99.5-100	141.5-142	149.5-150	159.5-160	179.5-180	189.5-190	209.5-210	229.5-230	239.5-240	249.5-250	259.5-260	269.5-270	279.5-280	289.5-290	298.5-299	310-310.5	319.5-320	339.5-340	359.5-360	389.5-390	399.5-400	409.5-410
PLANKTONIC POPULATION	4600	7100	21000	3300	7200	8000	25000	17000	25000	18000	34000	4900	14000	9500	16000	9100	3000	4100	10000	1900	30000	7300	5300	10000	3600	4300	25000
(%)																											
Globigerina bulloides	17	17	13	17	19	27	15	18	38	24	28	17	21	23	26	25	13	28	14	26	11	22	31	21	6	.3	28
digitata						3				1	.6	2	.5	7		5	5	2	1					1	6		3
eggeri	14	20	20	10	9	6	51	40	24	16	7	17	26	17	13	16	12	4	23	6	68	22	5	11	1	13	24
inflata	6				5	23	1	1	1	8	8	7	8	11	11	9	22	6	7	11		3	1	11	5	10	1
pachyderma	10	14	9	6	3	4	6	16	17	7	1	1	8	8	5	2	1	2	3	4	.4	5	1	4		2	1
quinqueloba	4	3	13	6	19	9	18	5	4	1	2	.7	5	5	6	1	5	5	5	10	11	3	4	3	4	9	4
radians																											
Globigerinella aequilateralis						.4				.4	2	1	3	3	.4	2	1	1	2	1	4	4	3	3	8	3	5
Globigerinita glutinata	7	10	15	12	14	8	.3	2	4	.7		3	4	7	11	6	8	9	10	11	.4		4	6	3	5	3
Globigerinoides conglobata																											
rubra, etc.	38	28	16	32	13	8	3	3	3	23	32	34	13	15	16	25	12	38	25	22		33	33	25	57	32	25
(typical G rubra present)											x	x	x			x	x		x				x				
sacculifera												3	.7	7	3	6	1		3								
tenella				7	4	1	.3			.7	2	3	2	.3	5	1	1	.4	4				6	4	.4	4	5
Globorotalia punctulata																											
scitula	2	8	14	9	14	4	3	8	5	4	5	.7	2	2	1	2	.3	1	1	7		2	8	8	7	3	.3
truncatulinoides	1						.3			4	4	3	2														
Hastigerina pelagica											.6	.3															
Orbulina universa	1			1		6	2	7	4	10	7	7	4	7	2	4	23	3	5	1	5	5	4	3	8	6	2
BENTHONIC POPULATION (actual numbers)	24	47	97	9	44	98	9	38	49	18	5	7	13	30	31	10	13	5	37	12	6	5	4	5	0	2	19
Articulina tubulosa & vars	6	10	20	3	8	35	3	3	1	2		3	7	9	13			2	27			2		4		2	7
Bulimina aculeata																	6										
Cassidulina crassa							1																				
cf sicula		8	1		1	1																					
Chilostomella mediterranensis								2	2			3															
Cibicides kullenbergi	2							5	11	2			2														
Eggerella bradyi, etc							1	7	11	3	2			3	5	1	1	1								1	
Globobulimina affinis																					5						
Glomospira charoides						3																					
Gyroidina altiformis ?														4	4												6
delicata							1	9	14	2				6													
cf neosoldanii														3	5	1		2	4								
Miliolidae			9			3			1	2							2			1							
Miliolinella circularis	3	14	19	4	12	50					1																
Pseudoeponides umbonatus var								5	1	1				10	2	7	1		1				3				5
Pullenia bulloides									1					2	1												
quinqueloba							2																	1			
Pyrgo lucernula			1					3	5	5																	
murrhina	6	8	21	1	5														1	10		2					
Quinqueloculina aff lamarckiana	4	4	20		15	1											2		4								
Robertina translucens					1	1				1	1		3														
Virgulina complanata																											
mexicana																											
Miscellaneous spp	1	2	6	1	2	3		3	2		1	1	1	3	1		1			1			1				
spp listed elsewhere	2	1				1	1	1								1						1					

SAMPLE	44	46	48	49	52	53	54	55	56	57	58	59	60	61	64	65	66	67	68	69	70	71	72	73	74	76	77
DISTANCE FROM TOP (CM)	419.5-420	439.5-440	451-451.5	459-459.5	489-489.5	493-493.5	499.5-500	509.5-510	519.5-520	530-530.5	539.5-540	549.5-550	559.5-560	569.5-570	599.5-600	609.5-610	619.5-620	629.5-630	639.5-640	649.5-650	659.5-660	669.5-670	679-679.5	689.5-690	699.5-700	719.5-720	729.5-730
PLANKTONIC POPULATION	62000	6400	14000	12000	38000	34000	12000	3000	8500	5900	16000	26000	28000	6100	6000	5400	3200	16000	12000	18000	9500	21000	25000	24000	14000	9900	12000
(%)																											
Globigerina bulloides	14	19	47	44	36	44	11	27	27	31	.8	42	15	26	29	32	18	36	35	27	25	29	53	19	22	21	12
digitata		5	4	2			.3	.5		1					4	.6		1			.3	1					.3
eggeri	63	4	.6		13	6	7	5	1		34	33	27	10	3	1	1	3	3			10	7	20	14	18	18
inflata		5	2		16	27	9	5	1		7		10	13	1	2	5	26	6	1	.7	6	.3	3	1	8	6
pachyderma	.6				3		4	.3	1		18		12	10		1		4	2			4	1	16	10	6	5
quinqueloba	5	2	2	4	6	5	5	11	14	12	4	11	5	4	5	6	18	6	1	2	6	2	5	5	5	9	4
radians		.5						2	2	2					.8		2	.4	.3		1		1				
Globigerinella aequilateralis		1	6	3	2	1		2	5	6	1	3	2	.5	5	.3	.5	3	4	4	10	5	4	.3	2	1	3
Globigerinita glutinata	.6	4	4	15	3	1	5	16	7	9	1		5	7	9	4	8		3	22	10	4		3	1	2	2
Globigerinoides conglobata			1													.6											
rubra, etc.	9.	53	27	26	9	8	51	27	36	33	14	7	17	20	36	44	42	15	31	40	39	24	16	26	33	29	38
(typical G rubra present)			x			x						x										x	x				
sacculifera				2						2										.4		6					
tenella	2	.7	5	2	1	.4	.3	1	2	1	1	.5	5	2	5	1		1	4	.5	3	1	.5	2	4		1
Globorotalia punctulata																5											
scitula	.6	5		.3					2		.4		.7	7	.5	.3	2	3	7		.3	2		4	5	5	7
truncatulinoides																											
Hastigerina pelagica										.3																	
Orbulina universa	5	5	5	1	13	7	7	3	2	2	1	3	.5		2	3	3	1	3	3	4	6	12	1	3	.3	3
BENTHONIC POPULATION (actual numbers)	48	7	5	14	1	2	27	7	4	6	10	0	70	26	16	23	10	28	13	2	10	5	0	26	29	23	13
Articulina tubulosa & vars		1	2					3	1				10	5	6		10	2	1	1	1	3		12	17	13	6
Bulimina aculeata																											
Cassidulina crassa				3											3												
cf sicula																											
Chilostomella mediterranensis			1								5							14									
Cibicides kullenbergi	3																										
Eggerella bradyi, etc			1	1						1			8	2	1	2			1		2	1		7	6	2	1
Globobulimina affinis											1		1	1													
Glomospira charoides																											
Gyroidina altiformis ?	6																										
delicata																											
cf neosoldanii		1									1			1				2	2	1	7	1			1	2	
Miliolidae			1	2				1	1				11	2	3	15		4	8					4	2	2	2
Miliolinella circularis									1																		
Pseudoeponides umbonatus var	24			5	1	2	27	3	1	4	3		32	5	3	3									1	1	
Pullenia bulloides																											
quinqueloba														1													
Pyrgo lucernula														3		1											
murrhina													1	2													
Quinqueloculina aff lamarckiana																											
Robertina translucens																											
Virgulina complanata				2									1														
mexicana																		4									
Miscellaneous spp	15	5								1			5	4		2		2	1					2	1	3	4
spp listed elsewhere				1									1											1	1		

TABLE 18. Distribution of Foraminifera in selected samples from Core 197.

CORE 198

SAMPLE	1	2	3	4	5	6	7	11	12	18	23	25	26	28	29	33	36	39	41	43	44	46	52	54	58	60	61	62	65	66	69	72	73	74	77	79	82	84	86	89	90	93	94	96	97	98	99	100	101	102	103	104	105	106	107	109	110	111	114	115	118
DEPTH FROM TOP (CM)	1-1.5	9.5-10	19.5-20	29.5-30	39.5-40	49.5-50	59.5-60	97.5-98	109.5-110	169.5-170	219.5-220	239.5-240	249.5-250	269.5-270	279.5-280	319.5-320	349.5-350	379.5-380	399.5-400	419.5-420	429-429.5	449.5-450	508.5-509	529.5-530	570.5-571	589.5-590	599.5-600	609.5-610	629.5-630	639.5-640	669.5-670	699.5-700	709.5-710	719.5-720	749.5-750	769.5-770	799.5-800	819.5-820	839.5-840	869.5-870	879.5-880	899.5-900	909.5-910	929.5-930	939.5-940	949.5-950	959.5-960	969.5-970	978.5-979	989-989.5	999.5-1000	1009.5-1010	1019.5-1020	1029.5-1030	1039.5-1040	1061-1061.5	1069.5-1070	1079.5-1080	1109.5-1110	1119.5-1120	1148.5-1149
PLANKTONIC POPULATION (%)	460	2000	1900	2100	2100	40	2600	890	3800	5200	8800	1100	8400	6000	1400	3700	1200	3200	1400	2800	1700	9000	4900	4100	1200	5000	15000	4100	1400	860	3500	2400	6400	3000	5100	4900	7700	4300	1900	2100	4700	24000	22000	17000	2700		3700	7600	2100	12000	2200	7100	34000	5700	3000	4700	2100	2100	5000	2600	970
Globigerina bulloides	12	23	13	8	12	30	20	9	16	11	33	20	44	9	4	23	6	40	60	23	42	26	34	27	30	26	25	25	20		19	28	32	40	47	45	36	11	45	21	9	10	45	49	11	23	34	.8	25	.7	39	16	24	31	25	9	28	30	31	66	45
digitata															2		2												6	8	1	.7								4						.4	.4				1			3		.3					
eggeri	8	22	13	7	10	9	11	11	20	26	19	15	7	13	8	26	7	6	7	3	3	24	18	7	5	15	47	23	2		.7	21	27	28	17	29	29	39	27	5	51	67	30	28	6	4	3	14	9	16	2	9	60	21	7		12	2	13	3	5
inflata	15	10	13	21	20								6	15	57	11	46	13	.3	15	1	15	.3	17	3	2	21	15	8			7		.5	10	3				13	7				19	27	29	22	26	.5	1	19		8	20	2		3	8	.4	26
pachyderma	1	17	7	3	11	23	11	4	9	8	3	2	4	2		5	2	.7		1	.4	3			1	.3						2	2	8	4	12	3	11	11	1	6			9	2		.6				.4			13	1		10	1	.6	3	2
quinqueloba	1	2	2	.4	.6			19		.6	7	4	17	8	1	6	9	10	6	2	1	1		1	.3	.3	1	3	1			8	7	4	2	.5	8	9	1	2	8	12	23	.6	1	.7	.4	1		.3	2		11	2		1	5	6	5	2	1
radians																																			2	.6													.4												
Globigerinella aequilateralis	.4	.6		.6																	3	.5	.6		10	3		.4		1	7	2														.7		3				1			.3	6					
Globigerinita glutinata	10	3	10	2			6	22	5	7	11	9	6	7	5	7	1			.3	.5			.4	.3	6	3	.4	.3	.5		1	2	.5	4	3	11	7	7	3	7			3				3		5		.7	3	3	2	5	3	12	2	.3	7
Globigerinoides conglobata																				6								4	1	1	.5	.3	6																												
rubra, etc	49	21	29	42	43	27	36	2	38	35	14	30	.4	22	1	17	23	26	26	44	41	20	38	44	41	31		22	51	73	61	16	3		1	.6				32	2			1	40	28	1	25	34	32	33	28	1	10	30	59	38	2		12	5
(typical G rubra present)	x	x		x																			x			x					x	x	x																x	x		x				x					
sacculifera	.6		.4																											8	2	1																			.4	1									
tenella							.3																			6				1	1	2	16							2					3	2		1	3	8	4	.7		3		3					
Globorotalia scitula			2		2	11	15	33	12	12	13	14	19	24	3	4	4	4	.6	4	3	.5	1	3	2	3		3	4			7	5	18	13	2	13	11	9	6	10	10		6	11	1	6	.4			6			5	1		4	13	12	5	8
truncatulinoides	3	.6	10	14	.6																	9			1																	.3				8	.4	8		18	1	21			10	10					
Hastigerina pelagica																														1																															
Orbulina universa				2								5			18					1	5	1	8		6	7	3	4	6	6	8	3				4		12		14			2	3	6	5	25	4	2	3	9	3	.6	4	3	4		3	3	4	1
BENTHONIC POPULATION (actual numbers)	11	19	21	10	24	0	8	22	23	32	20	14	2	25	28	31	25	10	7	5	0	27	0	18	0	0	0	0	0	0	0	14	19	0	1	5	6	13	5	4	127	53	0	4	4	0	18	2	0	0	0	0	0	45	12	0	27	20	38	27	2
Articulina tubulosa & vars	1	6	7	4	6			3	4	6	3	3	1	14	8	11	6	1	2	4		27		18									1		1	1	1	3	3	3	123			4	1		8	2						43	11		18	13	9	27	2
Bolivina catanensis	1							1																																		1																			
dilitata dilitatissima																																										3																			
Bulimina exilis																																										8																			
Cassidulinoides tenuis								2																																	1	8																			
Chilostomella mediterranensis																																										7																			
Globobulimina ? sp																																										8																			
Gyroidina delicata																																									2	2																			
Miliolidae	1	2	3	1	1		3	2	6	7	6	3	1	1																		10	4			4	3	8			1	1			2									1				2			
Miliolinella circularis	4	10	9	5	16		5	2	11	18	9	8		9	19	20	17	8	5	1												1					1	1																			2				
Neoconorbina williamsoni	2																																																												
Pyrgo murrhina								1	2																								8																								3	3	27		
Pyrgoella sphaera																																1						2																							
Quinqueloculina aff lamarckiana											2																																																		
Robertina translucens																	1	1																													3								1		1				
Virgulina mexicana																																										2																			
Miscellaneous spp	1	1	2		1			7		1					1		1															2	6				1	1		1		6			1		7							1			2	1	2		
spp listed elsewhere	1							4						1																												7															1	1			

TABLE 19. Distribution of Foraminifera in selected samples from Core 198.

(424)

CORE 199

SAMPLE	1	2	6	9	11	12	14	16	19	23	28	30	33	35	36	41	43	45	50	51	53	54	56	57	59	60	62	63	66	67	68	69	73	74	75	76	77	78	79	80	81	83	85	86	91	94
DEPTH FROM TOP (CM)	0-0.5	9.5-10	45.5-46	81.5-82	92.5-93	103.5-104	123.5-124	139.5-140	169.5-170	205.5-206	255.5-256	276.5-277	301.5-302	310.5-311	317.5-318	362.5-363	383.5-384	403.5-404	442.5-443	452.5-453	469.5-470	473.5-474	492.5-493	499.5-500	519.5-520	529.5-530	549.5-550	559.5-560	589-589.5	599.5-600	609.5-610	619.5-620	656.5-657	666.5-667	676.5-677	686.5-687	696.5-697	704.5-705	713.5-714	723.5-724	731.5-732	749.5-750	767.5-768	779.5-780	827.5-828	846.5-847
PLANKTONIC POPULATION (%)	2400	1900	1800	1400	1500	2600	1600	2500	1200	2300	290	1300	3200	2500	500	830	430	1100	1100	1100	270	490	2900	1800	420	520	580	1700	520	1600	1500	3100	1600	470	1200	2900	1100	1200	890	1800	1500	1200	1100	960	800	410
Globigerina bulloides	23	21	20	28	29	32	13	18	24	36	24	60	34	40	47	38	5	44	43	24	36	27	25	17	31	38	33	29	45	33	41	32	54	35	26	43	29	28	26	14	39	20	11	11	10	24
digitata	1								3					1	1		.5			.4		3	.3		2	2	1					.4		.6	2	.6			6				1		2	3
eggeri	11	15	15	11	12	8	19	16	18	6	14	8	9	13	20	9	3	15	6	14	19	21	34	35	6	.4	9	25	12	18	5	14	2	4	4	12	9	2	2	18	4	10	11	4	4	6
inflata	6		2	4	5	1	6	4	6	11	12	15	13	12	3	1	3	7	2	7	7	17	14	11	10				10	1	14	10	13	27	22	11	8	19	4	22	23	26	13	24	29	24
pachyderma	2	6	1	3	1	.5	2	4		2	5	.6	1	5	8				1	1	6	3	4	1	4			11	10	15	2	13	1		.5	6	3	3		25	4	5	26	4	.5	2
quinqueloba	8	19	35	22	18	21	34	21	10	29	28	13	20	14	11	41	45	20	4	4	18	3	5	5	4	2	2	17	2	9	14	11	14	1	9	5	5	9	2	2	4	3	8	6	8	.7
radians																											.5								.3	.3										
Globigerinella aequilateralis																			3	3		.6		1	1	2	2										1	.3	4	1			1	3	2	1
Globigerinita glutinata	3	15	13	13	13	23	9	17	19	5	3			.3	.4		2	.7	.4			1			4	.6	2	6	1		7	5	1		5	9	7	11	11	3	2	.3		1	3	.7
Globigerinoides conglobata																												2	9									1	3				.4			
rubra, etc	33	11		4	4	3	.5	6	5	4	7	2	16	10	6	9	41	11	36	43	9	19	10	17	33	47	45	1	.4	.4			2	22	13	.3	23	9	22	7	14	13	18	31	27	27
(typical G rubra present)																									x	x	x																	x	x	
sacculifera	8																					.4				1																		1		
tenella	1	1					.3		1	.4	.3	.3				.5		.4		1			2	5	2	2	2	3	2						1		.5	2	2	2	2	1	.4	6	4	3
Globorotalia scitula	1	12	13	15	18	12	16	14	13	6	6	1	7	5	4	1	.7	2	1	1	4	2	1	2	1		.5	5	8	23	14	12	10	7	15	11	13	12	7	4	4	9	10	5	3	.5
truncatulinoides	1																			.4		.4	3																6			9		2	5	7
Orbulina universa	2								4	.4	.7			.6					3	1		2	1	5	2	5	2				3	2	2	3	2	2	2	3	5	1	3	3		2	2	1
BENTHONIC POPULATION (actual numbers)	64	10	68	33	30	40	54	36	15	64	17	45	27	26	10	30	15	32	24	7	5	33	25	20	10	1	7	14	12	42	28	58	23	2	7	26	3	1	5	4	6	2	10	7	1	4
Articulina tubulosa & vars	2	1	15	1		1			2	3	1	4	5	3		18	4	14	1	4			9	8			1			5	6	20	16		3	2			1							
Bolivina albatrossi																				1		2	1		2				1																	
catanensis	1									1	1				1											1				2																
dilitata dilitatissima										1				1				1												2		2														
pseudoplicata																		1	4			1			1															2	3	2	4			1
Bulimina costata	1	1	4		1		2	3		1	1	13		2		1	2	1										4	2	1	1	1			1		1									
gibba	2																					1																								
Cassidulina carinata	1																1	2												2																
crassa										1													2				1																			
cf. sicula	1	2	9	3	11	15	30	2		30	7	6	13	7	4	1	3			1	1		1	9																						
Chilostomella mediterranensis		1														1						1	2					1																	1	
Cibicides aff. floridanus	11	1	2	2	1	1	7		1	6	2	8			2			2																												
kullenbergi	3																																		1	16			1							
Eggerella bradyi, etc	1																													1				1		1		1								
Elphidium crispum	2																					2																								
pulvereum										1	2			1								2																								
Globobulimina affinis	1	1						9	1													1	4	3																						
pseudospinescens								3		6		3	1																																	
Gyroidina altiformis	1																	1												1																
cf. neosoldanii	4																	1	3		2	2	3		4		2	1															2	1		3
Höglundina elegans	2																	1	1	1																										
Hyalinea balthica	1										1			1		1						1																								
Miliolidae	1		1	1	1				1			2		2		1					1	1			1				2	17	10	7	1				1		1		1		3	3		
Miliolinella circularis			1											2		3	2	1	5																				1				1	1		
Neoconorbina williamsoni									1		1					1																														
Nonion barleeanum, etc	2								1	1				1					1																											
Pseudoeponides umbonatus var.																												2	3			1														
Pullenia bulloides														1		1																								1						
quinqueloba										1		1		1					1									1																		
cf. riveroi													2	2															1	3	5	3	4			4										
Pyrgo anomala						1																1							1	1																
murrhina	1		21	11	3	18	9	15		4		5	1															1			5	19														
Quinqueloculina aff. lamarckiana		3	7	9	11	3	4			1																			1																	
Robertina translucens									1									2	2													1														
Robulus spp														1	1			2												1									1							
Rosalina aff. columbiensis	1																		2			1																								
Siphonina reticulata	4																																													
Spiroloculina canaliculata									1	1		1			1			1	1																											
Uvigerina mediterranea	3																					4																								
peregrina	3			1																										1																
Miscellaneous spp	8		8	4	2	1	1	4	3	4		2	3		1	2	3	2	1		1	8	2		2			4	1	4	1	3	2	1	2	3					2			2		
spp. listed elsewhere	7			1			1		3	2	1			1					2			5	1				3			1		1					1			1						

TABLE 20. Distribution of Foraminifera in selected sample from Core 199.

PLATES

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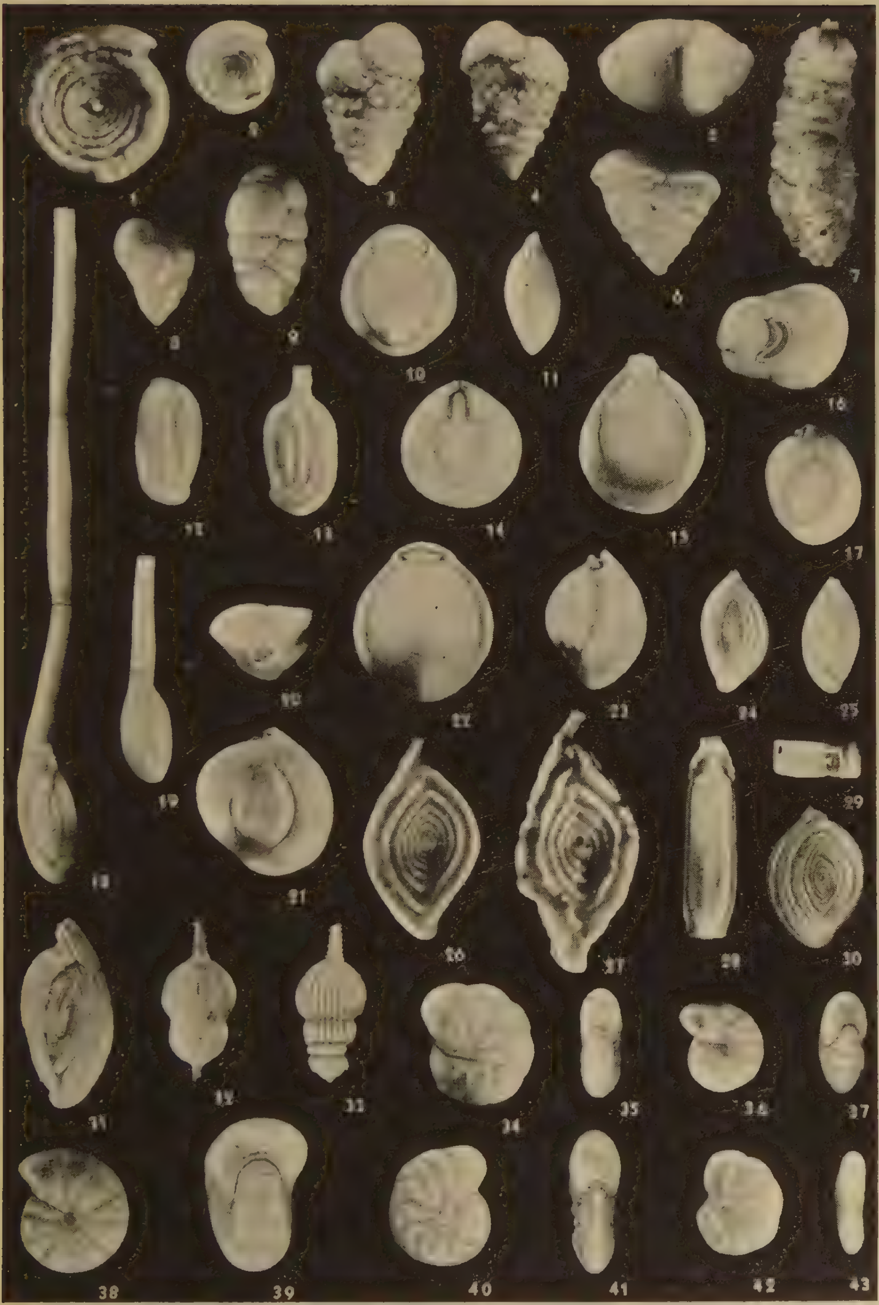
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PLATE 2

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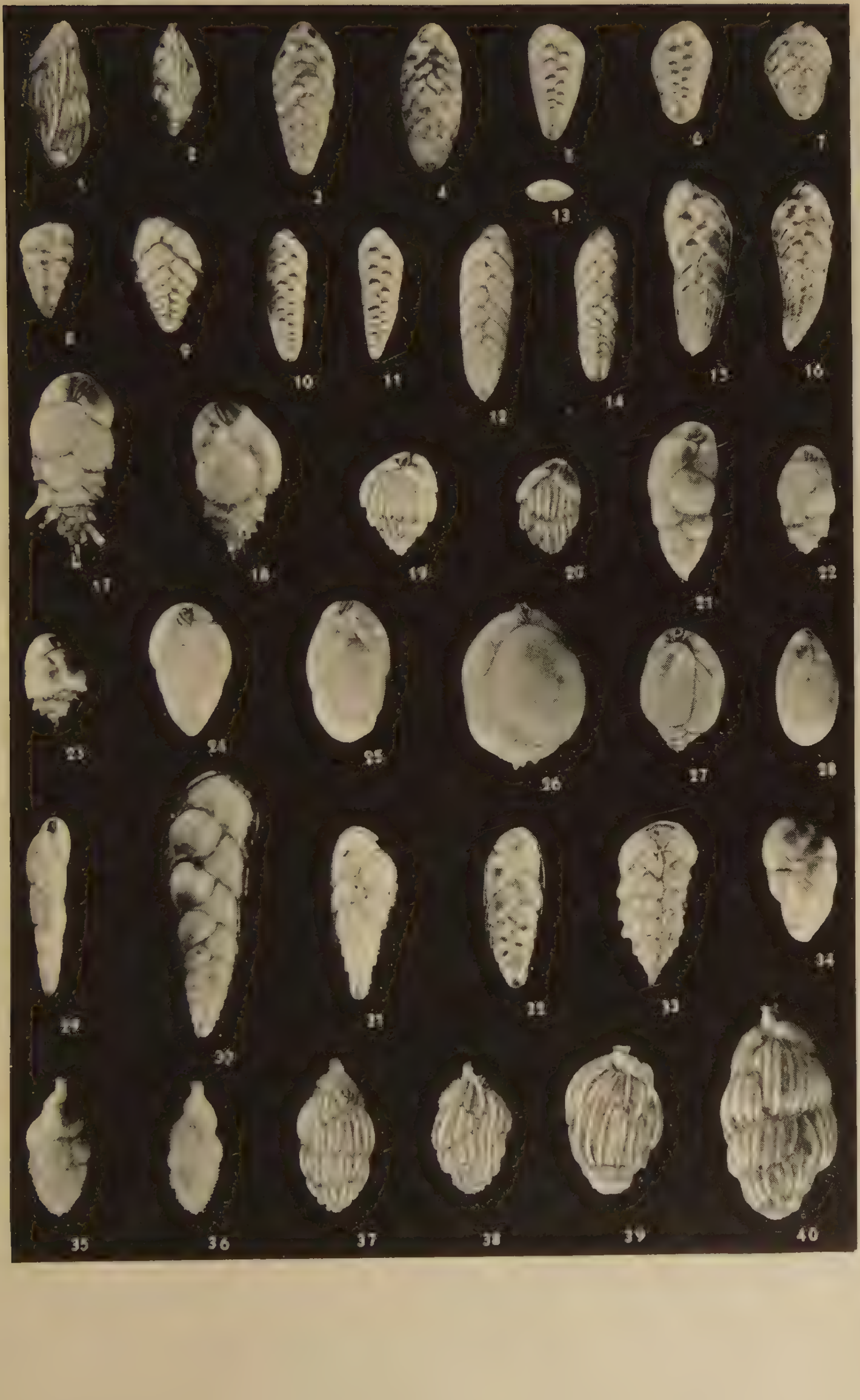
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PLATE 3

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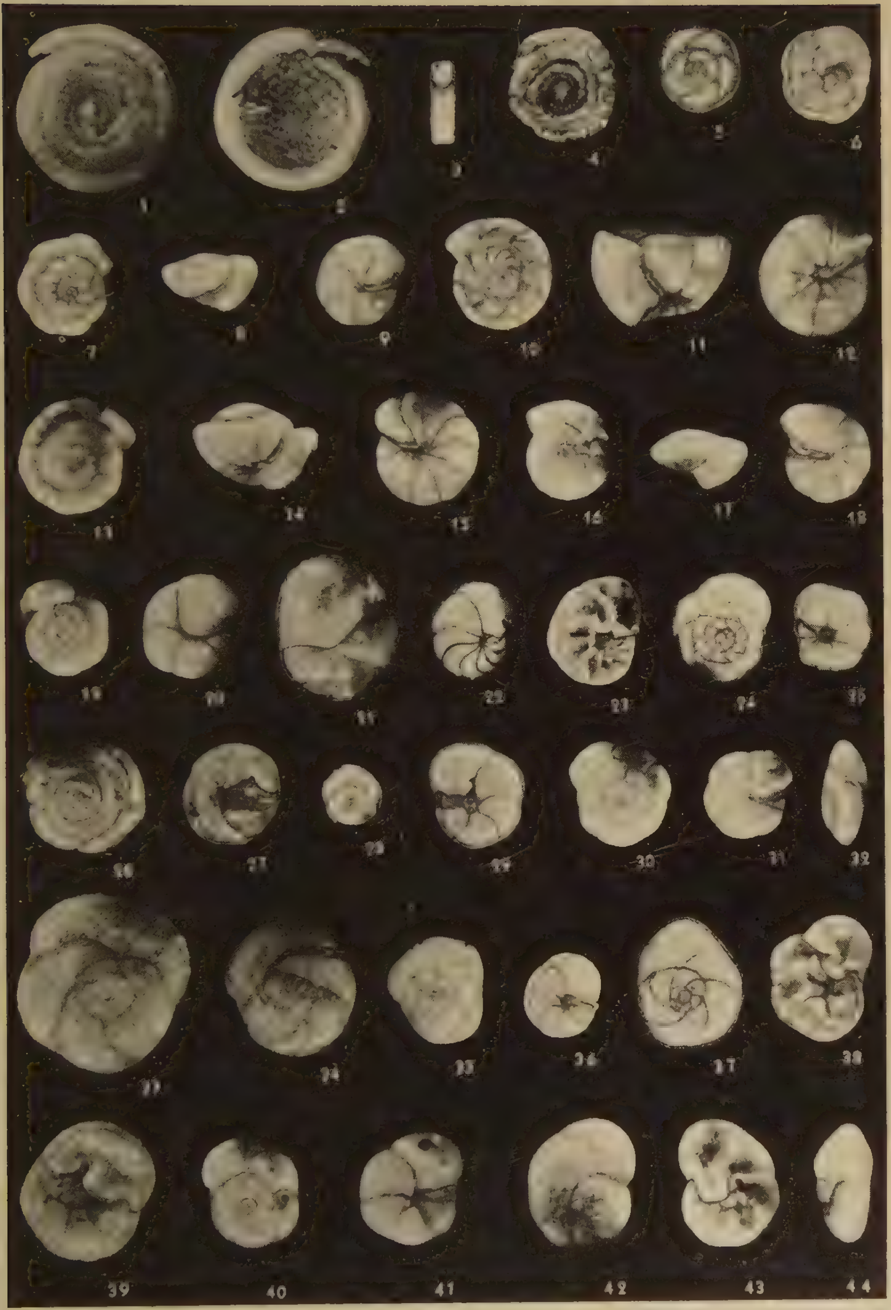
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PLATE 4

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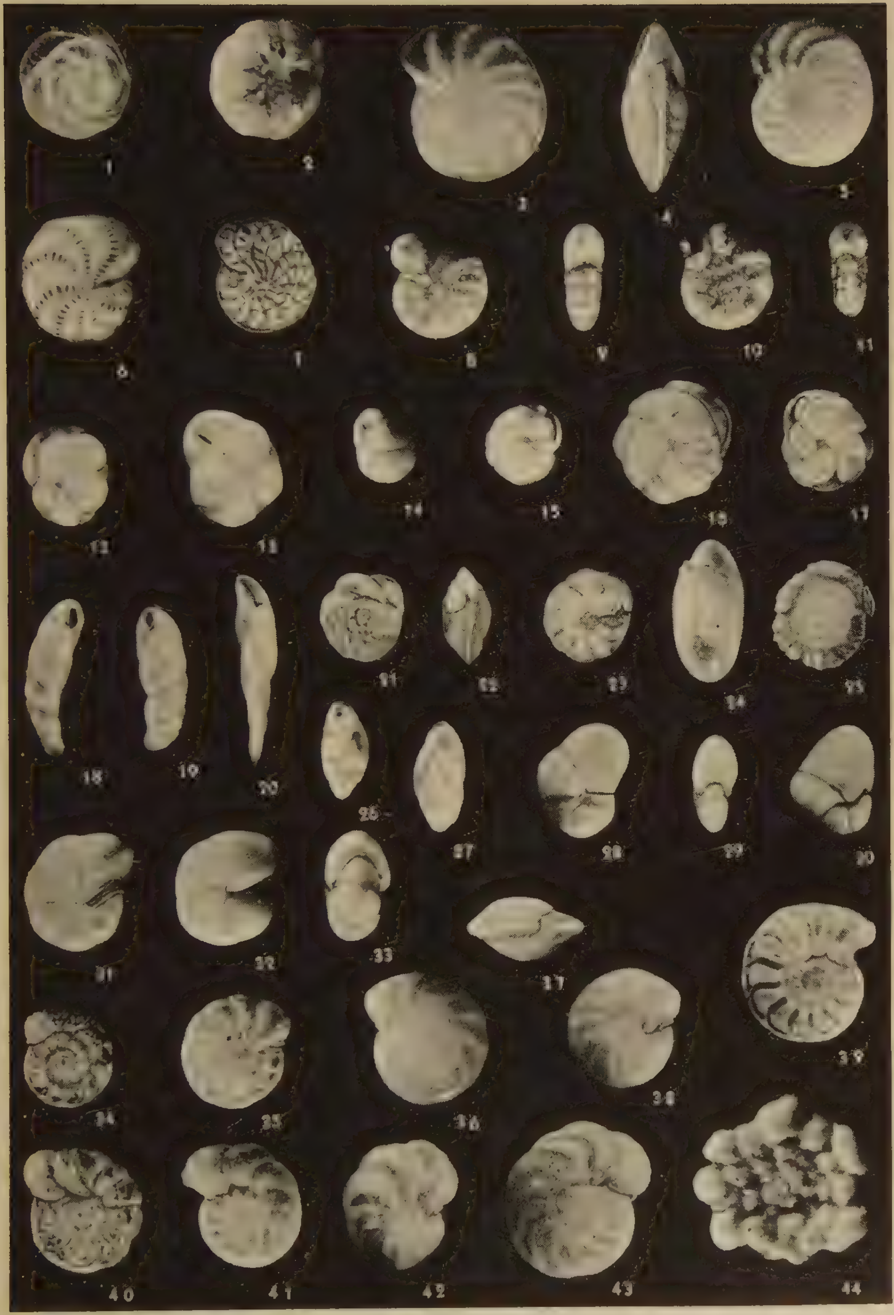
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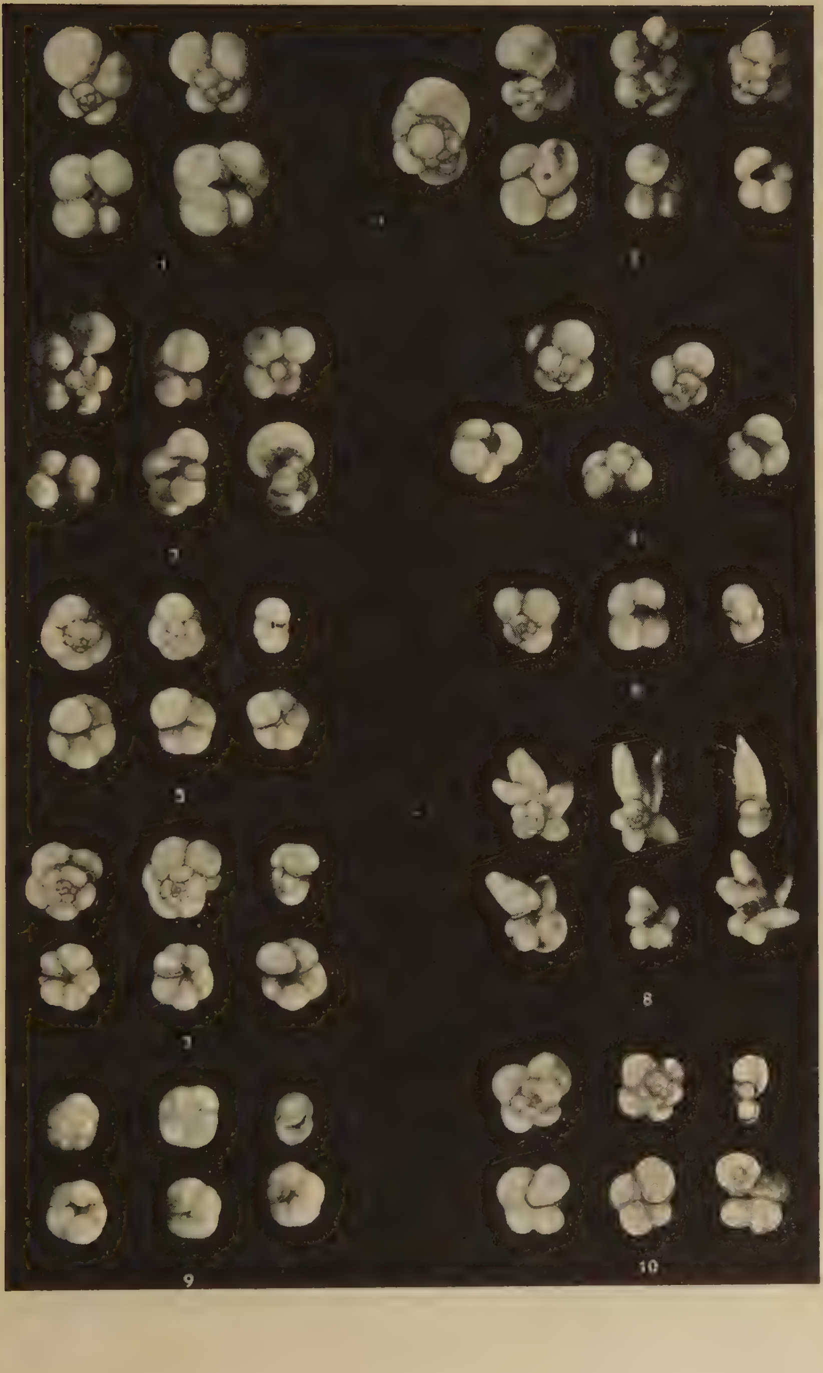
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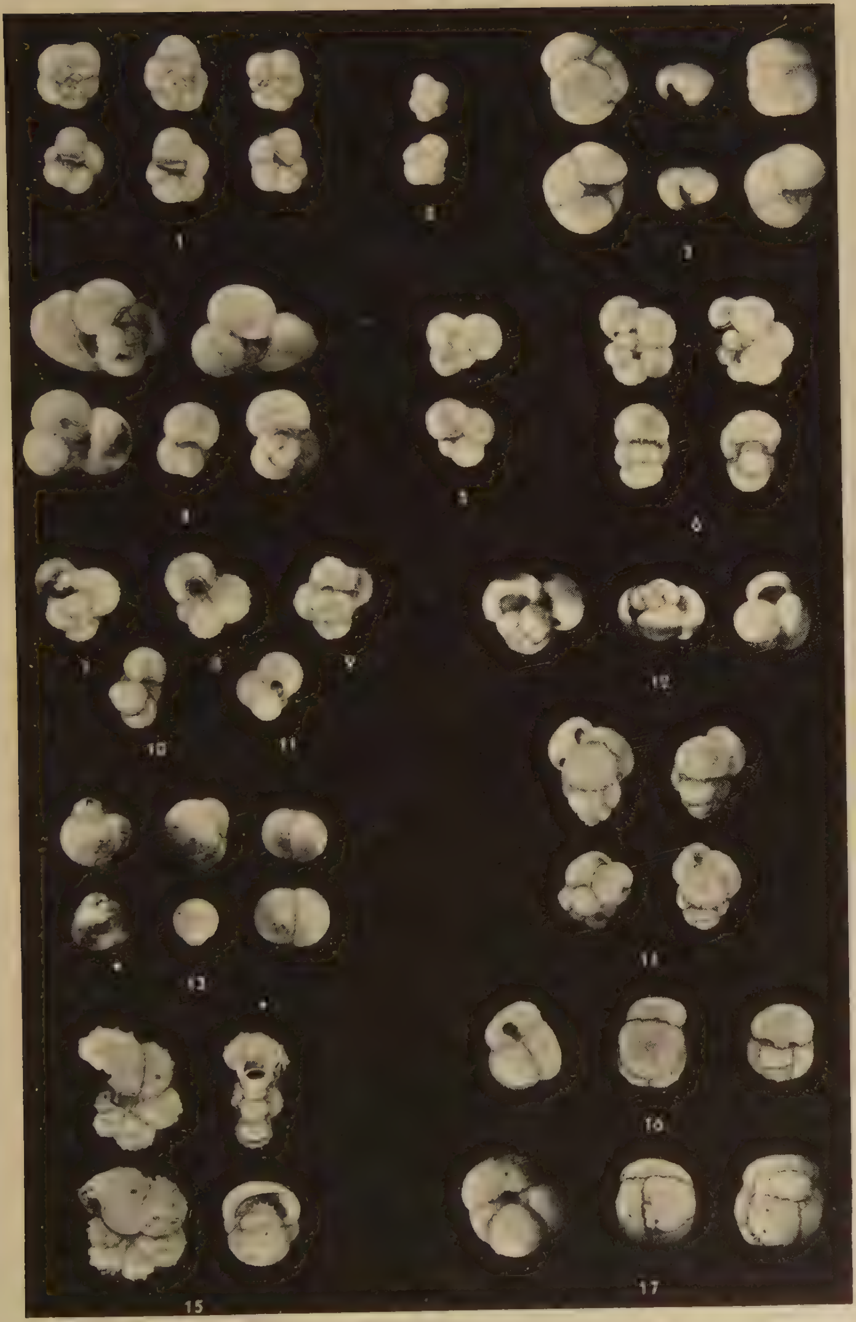
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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 29, NO. 2, PP. 153–163
FIGS. 1–3, JUNE, 1959

REFLECTIONS ON THE INTERPRETATION OF HEAVY MINERAL ANALYSES[1]

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ABSTRACT

The study of heavy minerals, an important field of endeavor for the sedimentary petrographer prior to 1940, has declined in recent years. This decline, caused primarily by the disappointing results of heavy mineral correlation, is regrettable because in regional stratigraphic and paleogeographic research the method is capable of contributing important information concerning the location and character of source areas and the distribution patterns of sediments. The following factors can modify the heavy mineral composition and limit the interpretation of the assemblage in terms of source area conditions: (1) weathering, (2) abrasion, (3) selective sorting, and (4) post-depositional solution. This paper attempts to show that (3) and (4) are of minor importance. In basins with a low rate of sediment supply and under conditions of intense weathering and reworking the others can strongly modify the composition of the heavy mineral assemblage. In basins of rapid deposition deriving their sediment in general from source areas with active erosion, the influence of all factors is negligible and the heavy mineral assemblage directly reflects the petrography of the source area. An example illustrates the type of problem for which heavy mineral analysis is of value. Problems of sediment source and distribution in the Mississippi valley and the Gulf Coastal Plain in the Cenzoic are a field where heavy mineral analysis is considered rewarding.

The author, during the past ten years, has had the opportunity to carry out a number of regional heavy mineral studies. The investigations have included both work on Recent sediments and on the laws that control the composition of heavy mineral assemblages, and studies of the stratigraphy and paleogeography of ancient basins. Some general thoughts concerning the interpretation of heavy mineral assemblages, based in part on this work, were presented in a symposium "Problems of correlating and interpreting sedimentary facies" at the Los Angeles meeting of the American Association of Petroleum Geologists, March 1958. The present paper is a further elaboration of the author's thoughts on the subject in the hope of stimulating interest in a topic that in his opinion has been neglected too much in recent years, particularly in the United States. The author wishes to thank M. N. Bramlette, P. D. Krynine and G. A. Rusnak for stimulating discussions on the subject.

Heavy mineral analysis is almost the oldest field of endeavor in sedimentary petrology. As early as the end of the 19th century publications on the heavy mineral content of sediments were remarkably abundant. An interesting history of sedimentary petrology prior to 1930 was given by Boswell (1933) and is well worth reading. It shows the stages of growth from a collector's interest in an inventory of all heavy minerals in a sample on through qualitative analysis for stratigraphic and petrologic studies, for example tracing the erosional history of a batholith (Brammall, 1928), to modern quantitative techniques. In the following years, preceding World War II, economic interest from the side of the petroleum industry stimulated a period of great activity, primarily in the use of heavy mineral analysis as a correlation tool. This is demonstrated by an impressive series of publications and an even larger quantity of unpublished material in oil company files. Even today, heavy mineral analysis and heavy mineral correlation are synonymous to many geologists. Recently, however, the interest in investigations of this nature has declined rapidly, and one might even say that they have fallen into disrepute.

In part this is due to the development of much more sensitive and convenient techniques for correlation, as for example micropaleontology, electric log analysis and pollen studies. These methods which have many scientific and practical advantages have in most cases obviated the need for mineral-

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[1] Manuscript received November 22, 1958.

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ogical correlation. Only occasionally the method is still applied (Feo-Codecido 1956).

This, however, is not the only reason for the decrease in interest in the field. Mineral zones are often broad and poorly defined and have a disconcerting habit of crossing other markers at high angles. A good example is Cogen's study of the Gulf Coast Tertiary (1940). Unfortunately, geologists have rarely stopped to ask why heavy mineral zones behave in this peculiar way, but have discarded their use instead. It is the author's opinion that this attitude is not justified and that in modern geology the study of heavy minerals in sediments has a definite and important place. It the purpose of the paper to argue in favor of this viewpoint.

In recent years the interest in broad regional studies of the paleogeography and facies distribution of entire depositional basins has increased enormously. Such studies are designed to provide detailed descriptions of the lithology of the basin and of its tectonic and depositional history. They have proved to be geologically rewarding and have considerable economic importance because they are useful for a better understanding of oil generation and migration. In order to obtain the sought-for understanding of the depositional history, such studies require information concerning the sources of sediments, the morphological, climatological and petrographical character of the source areas, and the distribution patterns of the detrital materials in the basin. In this respect the mineralogical analysis of both the light and heavy detrital fraction of the sediments is of great value. The unraveling of the complex erosional history of a sediment source and of shifts in drainage patterns by these means have been found helpful in many cases. Light minerals are most useful when the source area consists mainly of sedimentary or low rank metamorphic rocks, for example a mountain range in its earliest stage of uplift and erosion. Heavy mineral studies, on the other hand, are most useful when erosion has proceeded to deeper metamorphic and igneous rocks. Sometimes, with this method, both the erosional and tectonic history of the surrounding land mass and the depositional history of the basin have been worked out simultaneously (van Andel, 1958).

For such studies we must be able to interpret the mineral assemblages found in the sediments in terms of the characteristics of the source rock. This implies the ability to eliminate or take into account all modifications the assemblages undergo between the source rock and the completed analysis. The four principal factors that may modify the mineral composition are: (1) weathering both in the source area and in the depositional basin; (2) mechanical destruction during transportation; (3) selective sorting of minerals according to size and density, and (4) chemical destruction after deposition. A fifth factor, the error associated with the procedures of sampling and analysis, need not be considered here.

The importance of modifications of the heavy mineral assemblage by weathering has been discussed and emphasized by many authors. A recent discussion of the problem was provided by Weyl (1952a). The effect of weathering is shown by a decrease of the less stable components, as for example (in approximate order) augite, hornblende and epidote, and a corresponding relative increase of the stable elements, kyanite, staurolite, tourmaline, zircon, and rutile. In extreme cases this process can supposedly convert a hornblende-epidote association into a kyanite-staurolite-zircon assemblage (Weyl, 1949). Although there is difference of opinion between various authors concerning the order of decreasing stability (see Pettijohn, 1957, table 95) and the conditions under which weathering takes place, it appears to be a well established fact that heavy minerals can indeed be selectively eliminated by weathering.

For the purpose of this paper the processes of weathering themselves are of less interest than the quantitative importance of weathering as a destructive agent in controlling the mineral composition of sediments in depositional basins. Admitting that weathering can modify the heavy mineral assemblage in the source area or after deposition, how often does this actually happen and to what extent?

A survey of the literature shows that although many assumed cases of weathering of heavy mineral assemblages have been described, an appreciable portion of them can be explained equally well as the result of mixing of sediments from various sources (van Andel, 1952). Of the remaining still impressive number of cases the most pronounced examples are found either in very permeable sands and gravels above the ground water table (see for example Weyl, 1951a), in intensely weathered podzolic soils in the temperate zone (e.g. Weyl, 1951b, van der Marel, 1949), or in areas under humid tropical conditions (Wahlstrom, 1948, Hübl, 1942, and others).

The detritus supplied from a source area, however, is not necessarily derived from the weathered crust. In tropical regions the thickness of the weathered crust can be great and the regolith can represent an appreciable quantity of sediment available for erosion. In temperate zones the thickness of the weathered crust is generally small and when erosion is sufficiently active to supply the large quantity of material required to fill a major depositional basin, fresh bedrock is generally exposed. In most rivers of the temperate zone weathered detritus appears to constitute a small part of the load only, but even in the tropics highly unstable mineral assemblages are often found in rivers draining deeply weathered areas (for example, New Guinea, van Rummelen, 1951; Guayana Shield, van Andel and Postma, 1954; Nile, Shukri, 1950). Krynine (1935) has shown that under conditions of severe tropical weathering arkoses can be formed. It may be noted in passing that the author is familiar with a number of comparisons of outcrop and subsurface samples from the same formation in tropical areas. No significant differences attributable to weathering have ever been observed.

Apparently, even conditions of intense weathering in the drainage basin of a river need not result in a stream of detritus which is devoid of or even deficient in unstable components. This is probably at least partly due to the fact that the dense vegetation in humid tropical areas restricts lateral erosion. There is emphasis on vertical erosion as soon as the relief is sufficiently pronounced to create rivers of enough competence to carry an abundance of sand-sized sediment and heavy minerals. Where relief is not great enough, the supply of sediment and consequently the rate of sedimentation in the basin will be very low.

This suggests that although weathering certainly may modify heavy mineral assemblages profoundly, its influence on the composition of sediments is negligible in basins with a moderate to rapid rate of deposition. On old cratons, weathering under tropical conditions may result in deep and complete alteration of the mineral assemblages. It is, however, a slow process, most active in areas of low relief, and its products will be important only in basins with a slow rate of deposition.

Another factor theoretically capable of modifying the composition of the heavy mineral assemblage is selective mechanical destruction during transportation. Laboratory experiments on the rates of wear of various mineral species show that there is considerable difference between different species in the susceptibility for wear (for a summary see Pettijohn, 1957, pp. 558–561). Studies of natural examples, however, have never demonstrated an appreciable effect of mechanical wear in rivers even with 600–1000 miles of transportation (Russell, 1939 for the Mississippi; van Andel, 1950 for the Rhine). Even for beaches where the total distance traveled by the particles may be many times greater than the distances attained in river transportation, no conclusive proof for the elimination or even reduction of minerals has been presented. Nevertheless, it can be assumed that very prolonged reworking may result in the destruction of the mechanically less stable elements, but the time and energy required are certainly very large.

The composition of the heavy mineral assemblage of a sediment can be modified by sorting according to density and size during transportation and deposition. Heavy minerals cover a wide range of densities from 2.89, the cutoff point in bromoform, to over 5.0. Sizes range from an approximate minimum of 0.03 mm to larger than 0.5 mm and many species show a preference for specific size ranges. Zircon and rutile, for example, are almost always very small. Consequently, very fine grained sediments tend to have assemblages rich in zircon (van Andel, 1954; Poole, 1958) which are the result of sorting, not of the presence of a zircon-rich source rock. A zircon assemblage, therefore, always requires a test for dependence on sorting. The study of siltstones and shales in general has been found unrewarding.

Many other minerals have preferred size ranges, which in general depend upon the particular size distribution of that mineral in the source rock. Pyroxenes, especially those derived from volcanic extrusives, are often large, but in other cases there is no preferred range or the pyroxenes are small. Epidotes are frequently concentrated in the finer grade. In some cases it is possible to use the size distribution of a mineral species as a varietal characteristic (van Andel, 1950).

The effects of sorting can be strong, when the assemblage contains species of widely divergent preferred ranges. In general, the influence of size is predominant; the influence of density is of minor importance. In the region of the Rhone delta, France, two heavy mineral associations occur; a pyroxene-hornblende-epidote assemblage in the delta and nearshore zone, and a hornblende-epidote assemblage in the offshore deposits. The source of the deltaic assemblage can be traced easily to the volcanics of the French Central Massif (pyroxene) and the French and Swiss Alps (hornblende and epidote). The source of the other assemblage is obscure, since lateral supply appears to be ruled out by the presence of very different assemblages on both sides of the delta along the coast of the Mediterranean (van Andel, 1956).

The analysis of the grain size distributions of the diagnostic minerals (which together make up more than 75 percent of the assemblages) shows that the pyroxenes are restricted to the coarsest fraction, the epidote to the finest, and the hornblende occupies an intermediate position (fig. 1). The three minerals have approximately the same density. Differentiation of this assemblage by size sorting will result in coarse lag deposits rich in pyroxene and fine differentiates with abundant epidote. A plot of all analyses from this region in terms of a three-mineral system, pyroxene-hornblende-epidote, shows a clear differentiation series starting from the average Rhone assemblage The series is closely related to the depositional facies of the samples (fig. 2). The deltaic deposits are mainly coarse grained, lag-type, beach, dune and river sands; the offshore sediments in general are fine grained end products of the sorting process. The regional distribution of heavy mineral associations apparently is not due to differences in source, but is the result of sorting of a highly heterogeneous original assemblage. It is clear that failure to recognize this situation in an ancient basin would result in completely erroneous conclusions concerning the location and character of sediment sources.

This example has been described at some length because it presents an unusually clear case of an often mentioned phenomenon. Fortunately, such cases are by no means common. The Mississippi delta, for example, shows no differences in mineral composition at all between sandy and clayey deposits. In fact, the heavy mineral assemblages in the entire Mississippi distributive province are strikingly homogeneous. Thus, while a test of grain size control is always necessary, it may be concluded that only rarely will this factor seriously impair the interpretation of heavy mineral distributions in terms of source areas and source area characteristics.

The last point requiring discussion is the post-depositional destruction of minerals, a process which Pettijohn (1941) has called intrastratal solution. This process can be taken to include both weathering at the site of deposition and solution occurring at greater depth below the water table, but for the present discussion the author prefers to restrict its meaning to the latter process.

There is no doubt that the process of intrastratal solution does indeed exist. Several well documented examples can be found in the literature (Bramlette, 1941; Weyl, 1952b) of cemented or concretionary parts of sandstones with a mineral assemblage much richer in unstable components than the surrounding rock. Since differences in source between the various parts of the same sand could be ruled out, intrastratal solution must be held responsible for the disappearance of the less stable minerals from the porous non-cemented parts of the deposit. The number of such cases is small, and as far as this author is aware no proof has ever been advanced that the process can also operate on a much larger scale involving

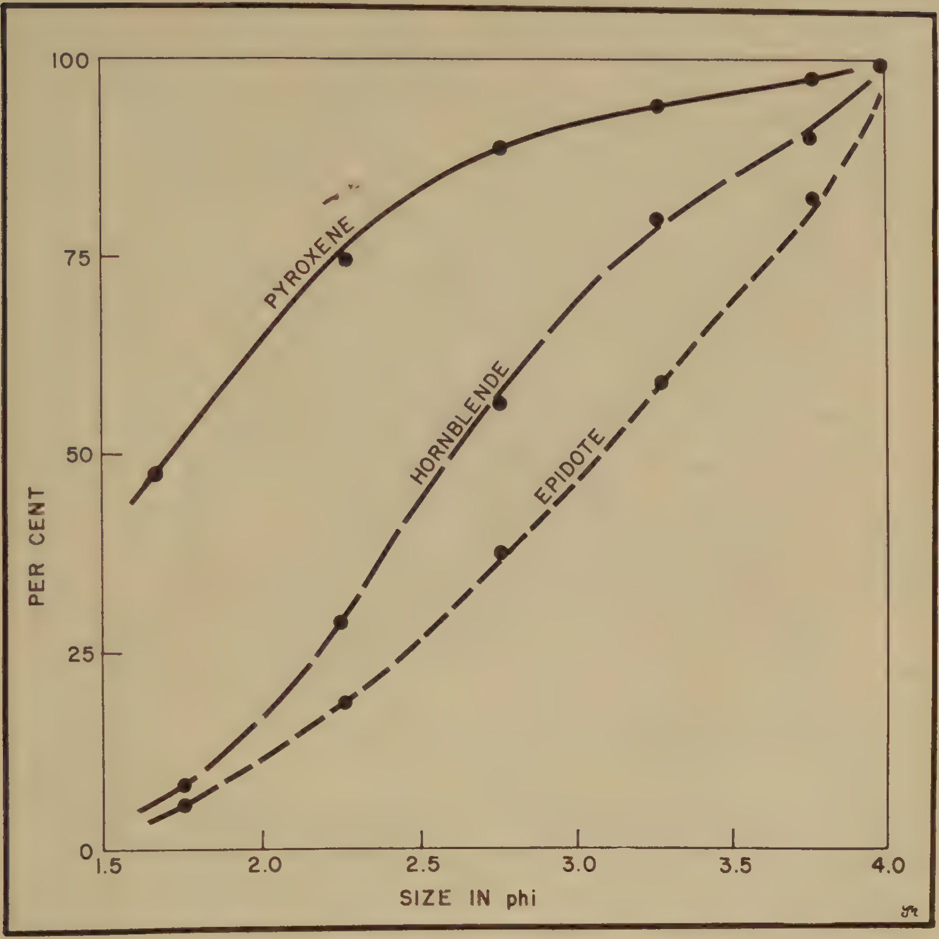

FIG. 1.—Cumulative grain size distributions of principal minerals pyroxene, hornblende and epidote in detritus supplied by the river Rhone. Data from table 6, van Andel, 1956.

great thicknesses and expanses of sediment.

Sediment sources are infinitely varied in mineralogical composition and any number of source rocks can contribute minerals to the depositional basin. Theoretically, the variety of possible heavy mineral assemblages is infinite. Nevertheless, the number of assemblages that usually is found is astonishingly small. Listing only the most important constituents the more common assemblages are the hornblende-epidote, epidote, kyanite-zircon, staurolite-zircon, garnet-zircon-tourmaline and zircon-tourmaline associations.

In many sedimentary basins these associations follow each other in a specific order which is from young to old, the one indicated above. Examples of such systematic sequences are found in the Alpine geosyncline (von Moos, 1935), Tunesia, Gulf of Mexico (Cogen, 1940), New Guinea, Java (Doeglas, 1940), Bighorn Basin (Stow, 1938), and Western Venezuela. The sequence generally occurs in Upper Cretaceous to Quaternary sediments. In pre-Cretaceous rocks the unstable minerals are rare and the dominant minerals are zircon, tourmaline and sometimes garnet.

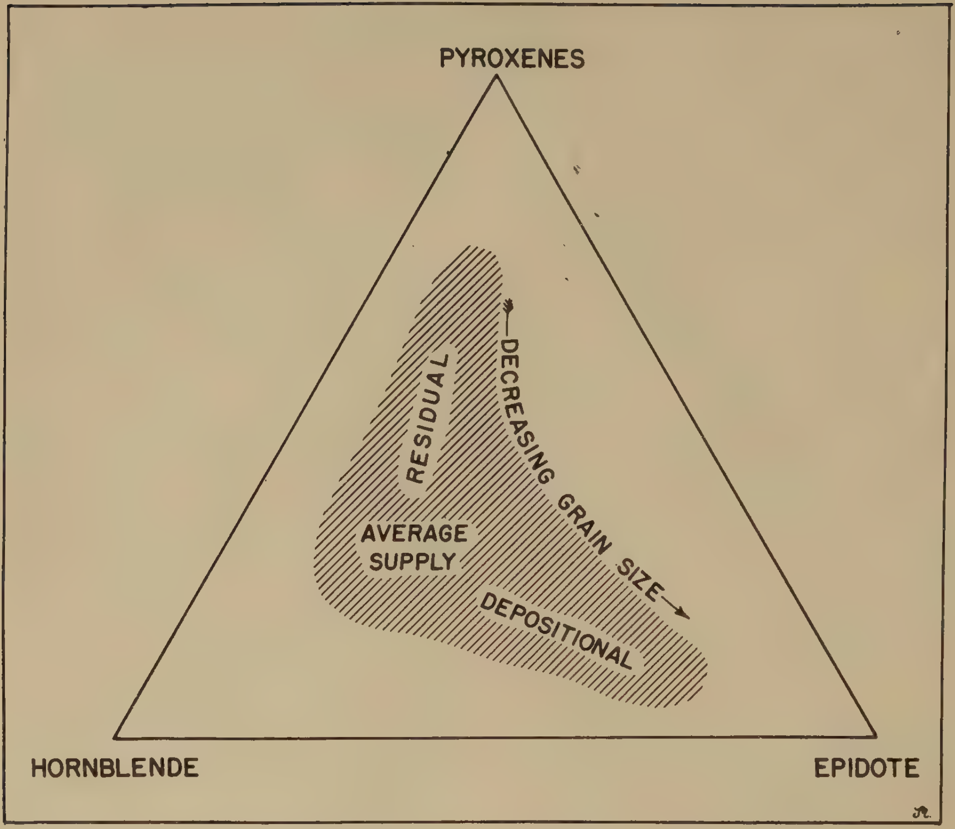

FIG. 2.—Triangle diagram of differentiation by sorting in the Rhone delta and offshore shelf of the heavy mineral assemblage supplied by the river Rhone: from fig. 16, van Andel, 1956.

Pettijohn (1941; 1957, p. 503–506, 514–520, 674–679) has discussed this phenomenon at length with the aid of a compilation of all published heavy mineral analysis. This compilation clearly demonstrates a general decrease of the richness of the suite with increasing age and an increase of the abundance of stable minerals. This persistence series of the individual minerals and the sequence of heavy mineral assemblages mentioned above are quite similar to the mineral stability series proposed by several authors (Pettijohn, 1957, table 95). The consideration of this and related facts has led Pettijohn to conclude that "it is possible, if not probable, that the older sediments have lost the less stable species by intrastratal solution" and that "the suggestion has been made that the heavy mineral zones are stability zones and owe their existence and character to selective removal of the less stable species in the deeper zones by intrastratal solution" (Pettijohn, 1957, p. 676–677). This is a statement of considerable importance because, if intrastratal solution does indeed have the importance suggested, most stratigraphic and paleogeographic conclusions based upon heavy mineral evidence would have no meaning.

Krynine (1942) has taken exception to such a wide application of the concept of intrastratal solution and has attributed the differences between heavy mineral zones to tectonic control through differences in source area petrography, morphology and weathering. His opinion has been ignored almost completely and the question deserves reexamination.

In this respect three sets of observations are of prime importance. The characteristic sequence of heavy mineral zones described above does not occur in all types of depositional basins but seems to be restricted to geosynclines. The more unstable members of the sequence appear during what Krynine (1942) has called the post-geosynclinal (orogenetic phase) and are the erosion products of the recently deformed and elevated mountain range. The unstable suites characterize foredeep ("molasse") deposits and the source areas are of the alpine type. Their first appearance, can, in many cases, be correlated quite closely with the phase of maximum diastrophism (van Andel, 1952) and the often stressed correlation between the heavy mineral zones and the geological time scale is true only in a very generalized sense. The epidote zone, for example, is of Pliocene age in New Guinea, Upper Oligocene-Miocene in Tunesia, Upper Oligocene in the alpine foredeep in Bavaria, Upper Eocene in Northwest Europe, Lower Oligocene in the sediments associated with the Andean foredeep in Western Venezuela. This suggests that diastrophism in the source area rather than mineral stability and intrastratal solution control the succession of zones, and that the minerals reflect the successive appearance by progressive uplift and erosion, of deeper metamorphic and igneous layers in the orogen.

If intrastratal solution would indeed be a major cause in the formation of heavy mineral zones, this should show at higher levels in an increase of corrosion structures before the final disappearance of the species. Such corrosion structures are easily observed (Edelman and Doeglas, 1932). For a number of unstable mineral zones in various parts of the world the author has investigated this possibility but has not observed any examples (van Andel, 1952). Similarly, it has been found impossible to establish a correlation between mineral stability and formation properties that would promote mineral solution as for example permeability and porosity.

The strongest argument in favor of the theory that heavy mineral zones are controlled by mineral stability rather than by provenance is that published analyses from many formations and many parts of the world show that unstable assemblages are indeed very rare in deposits of pre-Cretaceous time. However, it is very questionable whether a compilation of all published material, such as the one presented by Pettijohn (1941) in evidence of his intrastratal solution theory, is indeed reasonably representative for the heavy mineral suites of all rocks and facies of the geological column. A survey of the literature rather indicates the opposite. The Tertiary and Quaternary sediments that have been investigated for heavy minerals are predominantly of geosynclinal and foredeep facies and the less stable assemblages appear to be associated in general with orogenetic sources. Most of these studies have been carried out outside the United States, many of them in connection with unpublished petroleum exploration work. On the other hand, published information on the heavy minerals of pre-Cretaceous sediments is largely restricted to sediments in platform facies that were derived from cratonic sources. Much of this work was done in the United States. Geosynclinal deposits of pre-Cretaceous age are quite common, but those belonging to the post-orogenetic stage of development of the geosyncline have rarely been preserved and their heavy minerals have seldom been studied. Thus, it appears that the sample represented by the heavy mineral literature is heavily biased; in favor of geosynclinal post-orogenetic sediments for the Cenozoic, in favor of stable platform deposits for the pre-Cretaceous.

Based upon these considerations the author feels that much can be said for the following interpretation of heavy mineral zones, which follows Krynine and is different in emphasis from the one favored by Pettijohn. In a stable platform environment, where the sediments are derived from a cratonic, deeply weathered source of low relief, mineral assemblages subjected to considerable reworking are strongly altered and in general stable, except in the immediate vicinity of fresh outcrops of igneous and metamorphic rock. The absence of unstable minerals appears to be due not to intrastratal solution but to processes prior to deep burial. On the other hand, in geosynclinal and foredeep environments the mineral assemblage is essentially preserved in the composition inherited from the source area and the succession of mineral zones in such a basin reflects the formation, uplift and erosion of successively more complex rocks in the source area. Pronounced relief and rapid erosion in the source area with rapid burial in the depositional basin do not leave time for large scale elimination of unstable elements. The upward sequence of mineral zones reflects in inverse order the sequence: weathered layer—sedimentary and low rank metamorphics—high rank metamorphics and igneous, in the source areas. Numerous published studies of the heavy minerals of igneous and metamorphic rocks and, in particular, recent analyses by Fuechtbauer (oral communication) of the heavy mineral composition of conglomerates in the alpine foredeep in Bavaria demonstrate that the well known sequence of mineral zones can be explained completely in terms of the rocks available for erosion in the source area.

TABLE 1.—*Heavy mineral zones in the pre-Urals foredeep* (*after Sarkissian*)

Age		Region from north to south		
		Bashkir	Orenburg	Emba
TRIASSSIC		actinolite-glauconite	epidote	epidote
Upper Permian	U. Tartar	actinolite-glaucophane	hornblende	kyanite-staurolite (epidote)
	L. Tartar	garnet-tremolite-hornblende		
	U. Ufa	hornblende-pyroxene garnet	stable	stable
		epidote		
	L. Ufa	stable		

Consequently, the author is inclined to assign a minor role to intrastratal solution as a factor in the alteration of mineral assemblages. Heavy mineral assemblages can be altered profoundly if severe conditions and enough time are available, but this alteration appears to be a surface rather than a subsurface effect.

If this assumption is correct, then pre-Cretaceous series of geosynclinal sediments should possess the same sequence of stable and unstable associations found in many basins in the Tertiary, provided the post-orogenetic stage is included. Not many such complete series have been investigated. Recently, however, Sarkissian (1949, 1958) has published an extensive study of the geosynclinal deposits of Permian and Triassic age associated with the pre-Urals orogeny in Russia. His study shows that the post-orogenetic sediments carry the same highly unstable suites characteristic for Tertiary sediments of the same facies and thus form a strong argument in favor of the hypothesis developed here. His results have been summarized in table 1.

Several interesting examples of the use of heavy minerals for the interpretation of the geological and paleogeographical history of a basin have been published recently. The key to this type of study is a regional concept of heavy mineral distribution. In 1933 Edelman (quoted from Doeglas 1940) has defined the *sedimentary petrological province* as follows: "A sedimentary petrological province is a complex of sediments which by their geographical distribution, age and origin form a natural unit." The concept was originally derived from Baturin's work in the Caucasus. The application of this concept requires a regional and stratigraphic study of samples and puts much weight on a careful analysis of the interfingering and mixing of adjacent provinces and the features of provincial succession with time. Good examples of this method have been presented by Doeglas (1940) and by Cogen (1940). Much importance is attached to the regional approach and to the study of large numbers of samples with a wide coverage both in time and space.

This regional province concept has proved to be extremely fruitful in a large number of heavy mineral studies both of recent and ancient sediments of entire basins. It has, however, found little attention in the United States, where limited studies of a few samples in a localized area predominate in the literature.

An excellent example of the value of regional heavy mineral analysis for the paleogeography and geological history of a basin has recently been provided by Fuechtbauer (1953, 1958) in a study of the sources and distribution of sediments in the Oligocene-Miocene Molasse foredeep of the Alps in Bavaria. The deposits in this basin were largely derived from the mountain front in the south which, in the period investigated, had just passed through a major stage of deformation and uplift. The Middle Oligocene sediments of the basin all carry garnet assemblages derived from the south. By means of accessory minerals in the assemblages the various points can be identified from which the streams of sediment issued. Sediment distribution patterns are predominantly radial in great fans. In the Upper Oligocene the individual character of the various sources becomes more apparent and the distributive province at the far western end of the basin develops strongly. From this point of entrance a garnet-epidote association gradually spreads throughout the basin. The radial distribution pattern is replaced by an axial pattern with the development of an easterly regional dip. Gradually also the composition of the sediment changes and the garnet-epidote assemblage changes to an epidote assemblage. That this is the result of progressive erosion in the source area is shown by the analysis of heavy minerals in the accompanying conglomerates. A small contribution from the northeast is shown by the presence of a hornblende-containing assemblage in that part of the basin. Finally, during the upper Middle Miocene the eastward regional dip decreases and the sediment distribution pattern again becomes radial with fans spreading from various points along the southern margin of the basin. Schematically, the heavy mineral distributions and their changes with time have been indicated in figure 3 adapted from Fuechtbauer (1954).

Studies like the one just mentioned are based on large numbers of samples and a carefully established stratigraphic network. Given those prerequisites, however, they may greatly increase our understanding of sedimentation in a basin and consequently of its depositional history. It seems to the author that many problems in regional geology in the United States might well be fertile ground for regional heavy mineral study, and that the present lack of interest in the method, though understandable in view of the failure of so much localized work, is not justified. In conclusion one such problem that is of considerable importance and may be solved at least in part by mineralogical analysis may be described briefly.

This is the problem of the sources and history of the sediment supply for the Gulf of Mexico. After the early studies by Cogen (1940), Bornhauser (1940), and Goldstein (1942) no investigations of the sources of sediments, both ancient and modern, in this area have appeared. Cogen has shown that in this basin the same sequence of stable and unstable associations is found that has been described earlier in this paper. The youngest deposits investigated are Pliocene in age and contain an epidote assemblage with some hornblende. Information for the larger part of the Pleistocene is lacking until we come to the early Recent and Recent sediments which have complex sources. The modern Mississippi distributive province has a hornblende-pyroxene association. The source of these modern Mississippi sediments seems to be largely in the glacial deposits in its upper drainage basin. Horberg, in a series of studies, has shown that the early Pleistocene Upper Mississippi probably did not drain towards the Gulf of Mexico at all; and Potter (1955) has demonstrated that the Pliocene and early Pleistocene terrace deposits in Missouri and southern Illinois did not contain a modern Mississippi assemblage, but rather, exclusively locally-derived stable minerals. Potter considers that this assemblage is not the result of intensive weathering of an originally hornblende carrying suite. This reveals two interesting problems: (1) where did the Pliocene hornblende in the Gulf of Mexico come from if there was

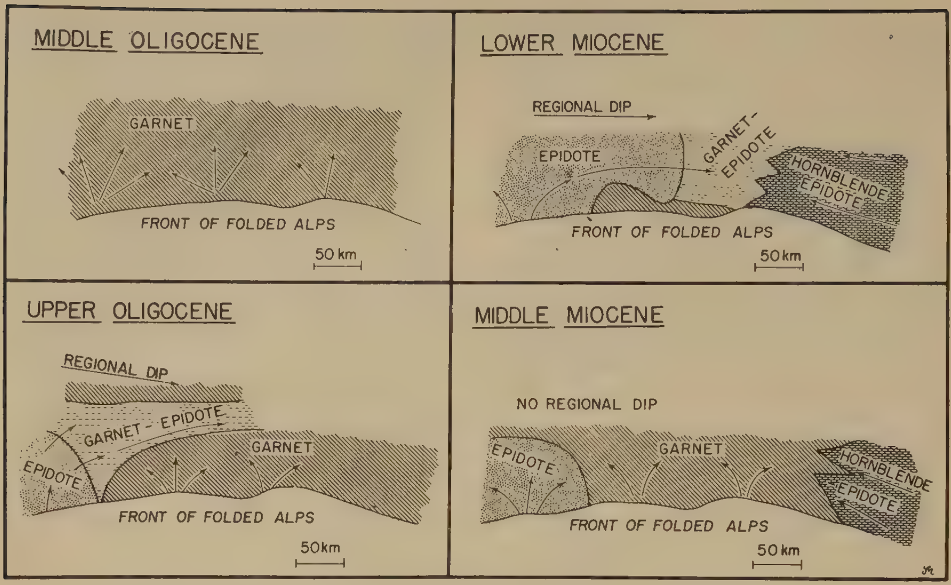
MIDDLE OLIGOCENE
GARNET
FRONT OF FOLDED ALPS
50 km
LOWER MIOCENE
REGIONAL DIP
EPIDOTE
GARNET-EPIDOTE
HORNBLENDE EPIDOTE
FRONT OF FOLDED ALPS
50 km
UPPER OLIGOCENE
REGIONAL DIP
GARNET - EPIDOTE
GARNET
EPIDOTE
FRONT OF FOLDED ALPS
50km
MIDDLE MIOCENE
NO REGIONAL DIP
EPIDOTE
GARNET
HORNBLENDE
EPIDOTE
FRONT OF FOLDED ALPS
50 km

FIG. 3.—Regional distribution of heavy mineral associations in the Molasse foredeep, Bavaria, Germany. Simplified after Fuechtbauer, 1954, fig. 2.

no hornblende supplied through the Mississippi valley, and (2) when did the present Mississippi assemblage come into being and what is the history of its distribution? It may be added that the situation is further complicated by the fact that in the few samples of Pleistocene Mississippi valley deposits that have been investigated, a hornblende assemblage occurs which is quite similar to the present Mississippi association but without the pyroxene.

Thus it seems that a regional study of the Pliocene and Pleistocene sediments of the Mississippi and Gulf Coast region can be expected to throw considerable light upon the regional development of sedimentation in that area. The present paper must be seen as an attempt to encourage sedimentary petrologists to undertake this and other similar problems. There is no doubt in the author's mind that this would be found rewarding.

REFERENCES

ANDEL, T. H., VAN, 1950, Provenance, transport and deposition of Rhine sediments. H. Veenman en Zonen, Wageningen, Netherlands, 129 p.

———, 1952, Zur Frage der Schwermineralverwitterung in Sedimenten: Erdöl und Kohle, v. 5, p. 100–104.

———, 1956, Recent sediments of the Rhone delta, II, Sources and deposition of heavy minerals: Geol. Mijnbouwk, Genootsch. Nederland Geol. Serie, v. 15, 3, p. 535–556.

———, 1958, Origin and classification of Cretaceous, Paleocene and Eocene sandstones in western Venezuela: Amer. Assoc. Petroleum Geologist Bull., v, 42, p. 734–763.

ANDEL, T. H., VAN, AND H. POSTMA, 1954, Recent sediments of the Gulf of Paria: Koninklijke Nederlandse Acad. Wetensch. Verhand., v. 20, p. 1–245.

BORNHAUSER, M., 1940, Heavy mineral associations in Quaternary and late Tertiary sediments of the Gulf Coast of Texas and Louisiana: Jour. Sedimentary Petrology, v. 10, p. 125–135.

BOSWELL, P. H. G., 1933, Mineralogy of sedimentary rocks. Thomas Murby, London.

BRAMLETTE, M. M., 1941, The stability of minerals in sandstone: Jour. Sedimentary Petrology, v. 11, p. 32–36.

BRAMMALL, A., 1928, Dartmoor detritals: a study in provenance: Geol. Assoc. Proc., v. 39, p. 27–48.

COGEN, W. M., 1940, Heavy mineral zones of Louisiana and Texas Gulf Coast sediments: Amer. Assoc. Petroleum Geologists Bull., v. 24, p. 2069–2101.

DOEGLAS, D. J., 1940, The importance of heavy mineral analysis for regional sedimentary petrology National Research Council, rep. Committee on Sedimentation, exhib. G., p. 102–121.

EDELMAN, C. H., AND D. J. DOEGLAS, 1932, Reliktstrukturen detritischer Pyroxenen und Amphibolen: Miner. Petrogr. Mitt., v. 42, p. 482–489.

FEO-CODECIDO, G., 1956, Heavy mineral techniques and their application to Venezuelan stratigraphy: Amer. Assoc. Petroleum Geologists Bull., v. 40, p. 984–1000.

FUECHTBAUER, H., 1953, Transport und Sedimentation der westlichen Alpenvorlandsmolasse: Heidelberger Beiträge Miner. Petrogr., v. 4, p. 26–53.

———, 1958, Die Schüttungen im Chatt und Aquitän der deutschen Alpenvorlandsmolasse. Eclog. Geol. Helvet. (in press).

GOLDSTEIN, A., 1942, Sedimentary petrologic provinces of the northern Gulf of Mexico: Jour. Sedimentary Petrology, v. 12, p. 77–84.

HUEBEL, H. H., 1942, Geochemische Untersuchung einer jung-tertiären Verwitterungsreihe: Deutsche Geol. Ges. Zeitschr., v. 94, p. 115.

KRYNINE, P. D., 1935, Arkose deposits in the humid tropics: Am. Jour. Sci, v. 29, p. 353–363.

———, 1942, Differential sedimentation and its products during one complete geosynclinal cycle: 1st Panamerican Congress Mining Engin. and Geol. Proc., v. 2, p. 537–582.

MAREL, H. W., VAN DER, 1949, Mineralogical composition of a heath podzol profile: Soil Sci., v. 67, p. 193–207.

MOOS, A., VON, 1935, Sedimentpetrografische Untersuchungen an Molassesandsteinen: Schweiz. Miner. Petrogr. Mitt., v. 15, p. 169–265.

PETTIJOHN, F. J., 1941, Persistence of heavy minerals and geologic age: Jour. Geol., v. 49, p. 610–625.

———, 1957, Sedimentary rocks. 2nd ed., Harper & Brothers, New York, 718 p.

POOLE, D. M., 1958, Heavy mineral variation in San Antonio and Mezquite bays of the central Texas coast: Jour. Sedimentary Petrology, v. 27, p. 65- 74.

POTTER, P. E., 1955, The petrology and origin of the Lafayette gravel: Jour. Geology, v. 63, p. 115–132.

RUMMELEN, F. F. F. H., VAN, 1951, Sand petrological investigations of terrace sands from some rivers 1–38, in Irian: Scient. News Letter, v. 3, p. 142–150.

RUSSELL, R. D., 1939, Recent marine sediments. Am. Assoc. Petroleum Geologists, Tulsa, p. 32-47.

SARKISSIAN, S. G., 1949, Petrographic—mineralogical investigation of the Upper Permian and Triassic variegated deposits of the pre-Urals region. Acad Sci U.S.S.R., Moscow, 191 p. (in Russian).

———, 1958, Upper Permian continental molasse of the pre-Urals region. Eclog. Geol. Helvet. (in press).

SHUKRI, N. M., 1950. The mineralogy of the Nile sediments: Quart. Jour. Geol. Soc. London, v. 105, p. 511–534.

STOW, M. H., 1938, Dating Cretaceous-Eocene tectonic movements in Bighorn basin by heavy minerals: Geol. Soc. America Bull., v. 49, p. 731–762.

WAHLSTROM, E., 1948, Pre-Fountain and recent weathering on Flagstaff Mountain near Boulder, Colorado: Geol. Soc. America Bull., v. 59, p. 1173.

WEYL, R., 1949, Jungtertiäre Schlotten im Zechstein von Lieth bei Elmshorn: Schr. Naturwiss. Ver. Schleswig-Holstein, v. 24, p. 74–80.

———, 1951a, Terrassengliederung und Schwermineralführung von Schotterablagerungen des südwestlichen Schwarzwaldes: Neues Jahrb. Geol., Pal., Miner., v. 9, p. 262–272.

WEYL, R., 1951b, Schwermineralverwitterung in Schleswig-Holsteinischen Böden: Schr. Naturwiss. Ver. Schleswig-Holstein, v. 25, p. 157–165.

———, 1952a, Zur Frage der Schwermineralverwitterung in Sedimenten: Erdöl und Kohle, v. 5, p. 29–33.

———, 1952b, Schwermineraluntersuchungen im Schleswig-Holsteinischen Jungtertiär: Deut. Geol. Ges. Zeitschr., v. 104, p. 99–133.

G. I. RODEN AND G. W. GROVES

RECENT OCEANOGRAPHIC INVESTIGATIONS IN THE GULF OF CALIFORNIA

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RECENT OCEANOGRAPHIC INVESTIGATIONS IN THE GULF OF CALIFORNIA

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ABSTRACT

Results of seven hydrographic cruises into the Gulf of California during 1956 and 1957 show that the water mass there is characteristic of Equatorial Pacific water though modified by intensive evaporation in surface layers. The combination of wind regime and complicated topographical features plays a predominant role in circulation, upwelling, distribution of temperature, and other hydrographic factors. Seasonal changes are large. An estimate of the water budget indicates that exchange between the Gulf and the Pacific Ocean is of the order of 10^6 m^3/sec. Evaporation in the Gulf is about 5×10^3 m^3/sec. Runoff and precipitation are negligible. Sea-level records were studied and interpreted in terms of geostrophic surface flow. Strong tidal currents in many parts of the Gulf are influencial in mixing the water.

Introduction. The oceanographic aspects of the Gulf of California, one of the least known marginal seas of the North Pacific, are both interesting and complex. Yet little oceanographic research has been done until recently. The Gulf is unique in that it is the only large evaporation basin in the Pacific Ocean. It is characterized by a large annual temperature range and by relatively high salinities. The tidal range at its inner end is impressive and so is the tidal bore that reaches far into the Río Colorado.

Prior to 1956, when the Scripps Institution of Oceanography in collaboration with the South Pacific Fisheries Investigations of the U. S. Fish and Wildlife Service decided to make a series of oceanographic cruises into the Gulf as part of the research conducted under the California Cooperative Oceanic Fisheries Investigations, only two hydrographic expeditions had been undertaken into this region. The first took place in 1889 with the ALBATROSS (Tanner, 1888) and the second, almost 50 years later, with the E. W. SCRIPPS (Sverdrup, 1941). Results from these two cruises and the meteorological aspects of the Gulf region were discussed recently (Roden, 1958).

The aims of the recent cruises into the Gulf from an oceanographic standpoint were twofold: to investigate the seasonal variation of

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temperature, salinity and oxygen in the upper layers and to determine whether or not any changes in the distribution of properties had taken place in the deeper part of the sea since the last survey in 1939. In addition there were biological investigations which will not be considered here.

Tides and sea level variations in the Gulf have not been studied in detail, but since they are important in understanding the circulation, a brief description of them will be found at the end of this paper.

Data. The stations occupied and the areas covered on the seven recent cruises into the Gulf are shown in Fig. 1 and Table I, respectively. On each hydrographic station, bottle casts were made and temperatures, salinities and oxygens were determined. Bathythermographs were lowered on each station and between stations. The data were processed by the Data Collection and Processing Group of the Scripps Institution of Oceanography; the tabulated data will be published in OCEANIC OBSERVATIONS OF THE PACIFIC, 1956 AND 1957. Sea surface temperatures at coastal stations were obtained from the U.S. Coast and Geodetic Survey (1956) and meteorological information was obtained from Servicio Meteorológico Mexicano (1937, 1938).

Seasonal Variation of Temperature, Salinity and Oxygen at the Surface. One of the outstanding features of the Gulf of California is the large annual range of sea surface temperatures; at Puerto Penasco in the north the range is about 16 C; at Cabo San Lucas in the south it is about 9 C (Table II). The pronounced seasonal temperature variation is not confined to coastal areas but occurs in offshore regions as well (Fig. 2); agreement between coastal and offshore temperatures is reasonably good. An interesting feature is an area of low temperatures around Isla Angel de la Guarda which is found throughout the year. Along the coast, temperatures are somewhat dependent upon upwelling; in winter low temperatures are generally found along the east coast and in summer along the west coast. There is little information on the year-to-year variation of temperature except that in 1957 temperatures appeared to be somewhat higher than in 1956. The seasonal variation of temperature extends downward from the surface to about 200 m, the average temperature in this depth range ranging between 14 C in winter to 18 C in summer over most of the Gulf.

The seasonal variation of salinity (Fig. 3) is surprisingly small and, except for the southernmost part, the annual range does not exceed 0.2‰. This contrasts sharply with results obtained from shore stations, where the seasonal range is of the order of 1‰ (U. S. Coast and Geodetic Survey, 1954; thus observations along the shore are not

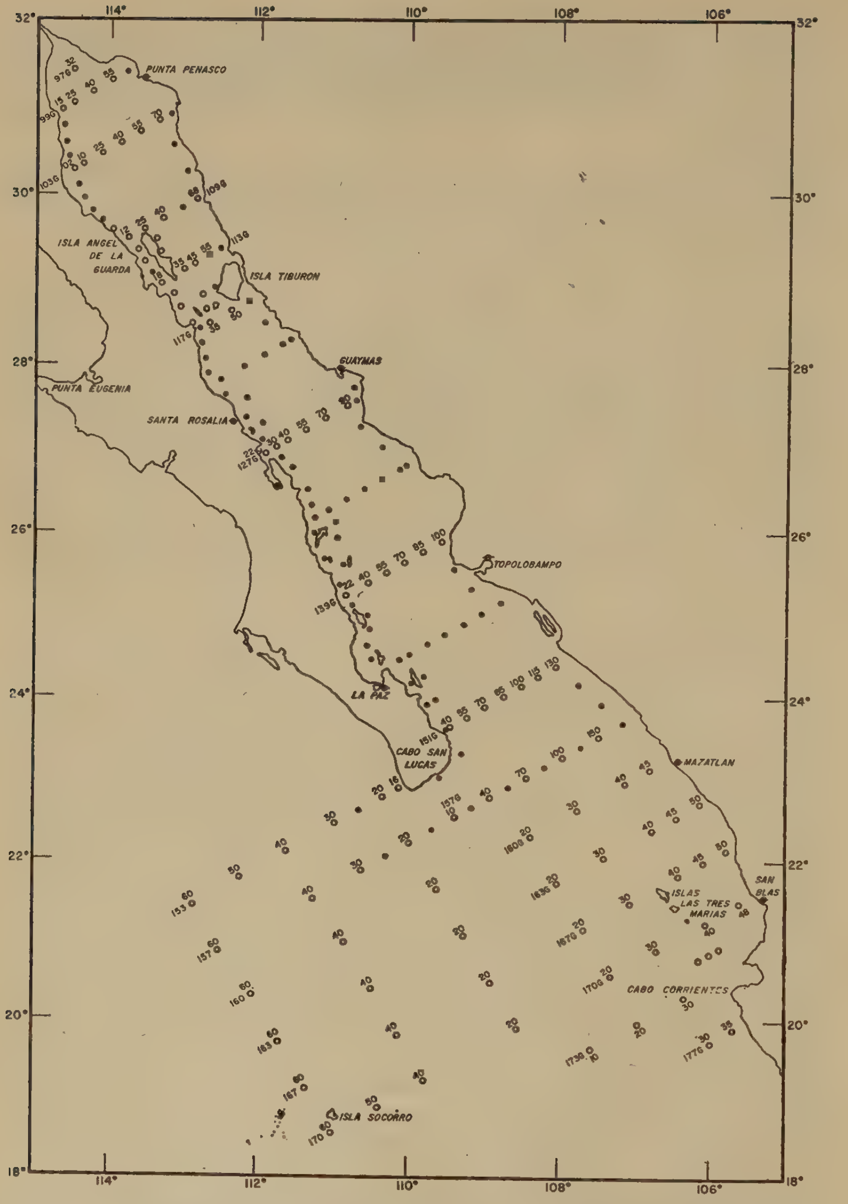
114°
112°
110°
108°
106°
32°
30°
28°
26°
24°
22°
20°
18°
PUNTA PENASCO
ISLA ANGEL DE LA GUARDA
ISLA TIBURON
GUAYMAS
PUNTA EUGENIA
SANTA ROSALIA
TOPOLOBAMPO
LA PAZ
CABO SAN LUCAS
MAZATLAN
SAN BLAS
ISLAS LAS TRES MARIAS
CABO CORRIENTES
ISLA SOCORRO

Figure 1. Stations occupied during recent Gulf cruises. Circles represent hydrographic stations, dots net-tow stations. Numbers refer to hydrographic stations.

TABLE I. CHRONOLOGICAL LIST OF HYDROGRAPHIC CRUISES INTO THE GULF OF CALIFORNIA.

Time	*Ship*	*Hydrographic casts* *Number*	*Hydrographic casts* *to depth*	*Properties observed*	*Area covered*
11 Mar.–7 Apr. 1889	ALBATROSS	28	bottom	temperature, salinity	Cabo San Lucas northward to Río Colorado.
13 Feb.–19 Mar. 1939	E. W. SCRIPPS	53	bottom	temperature, salinity, oxygen, calcium	Cabo San Lucas northward to Río Colorado.
6 Feb.–17 Feb. 1956	BLACK DOUGLAS	22	1200 m	temperature, salinity, oxygen	Cabo San Lucas northward to Isla Tiburón.
7 Apr.–23 Apr. 1956	BLACK DOUGLAS	40	600 m	temperature, salinity, oxygen	Cabo San Lucas northward to Río Colorado.
26 Nov.–16 Dec. 1956	HORIZON	59	bottom	temperature, salinity, oxygen	Cabo San Lucas southward to Isla Socorro and Cabo Corrientes.
8 Feb.–23 Feb. 1957	SPENCER F. BAIRD	67	bottom	temperature, salinity, oxygen	Cabo San Lucas northward to Isla Tiburón.
7 Apr.–23 Apr. 1957	BLACK DOUGLAS	37	600 m	temperature, salinity, oxygen	Cabo San Lucas northward to Río Colorado.
7 June–23 June 1957	STRANGER	57	600 m	temperature, salinity, oxygen	Cabo San Lucas northward to Río Colorado.
9 Aug.–26 Aug. 1957	STRANGER	57	600 m	temperature, salinity, oxygen	Cabo San Lucas northward to Río Colorado.

(457)

TABLE II. Sea surface temperatures (c) at shore stations

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*	*Range*
Puerto Peñasco, Son. (1952–1955) USCGS	14.9	15.8	17.8	20.6	23.8	26.3	29.7	31.2	31.0	28.4	22.0	17.1	23.2	16.3
Guaymas, Son. (1950–1953, 1957) USCGS	17.7	18.7	18.8	21.5	25.0	29.3	31.4	31.5	31.3	28.9	24.1	18.7	24.7	13.8
Mazatlán, Sin. (1953–1957) USCGS	21.4	20.1	20.5	21.6	24.1	28.2	29.5	30.0	29.9	28.5	25.1	22.0	25.1	9.9
Cabo San Lucas, B.C. (1957) SIO	20.8	20.5	—	20.6	23.1	23.6	25.9	28.2	29.0	—	26.2	24.4	24.2	(8.5)
La Paz, B.C. (1950–1957) USCGS	19.8	19.9	21.3	22.2	24.0	24.9	27.4	29.1	28.3	28.1	25.1	21.3	24.3	9.3

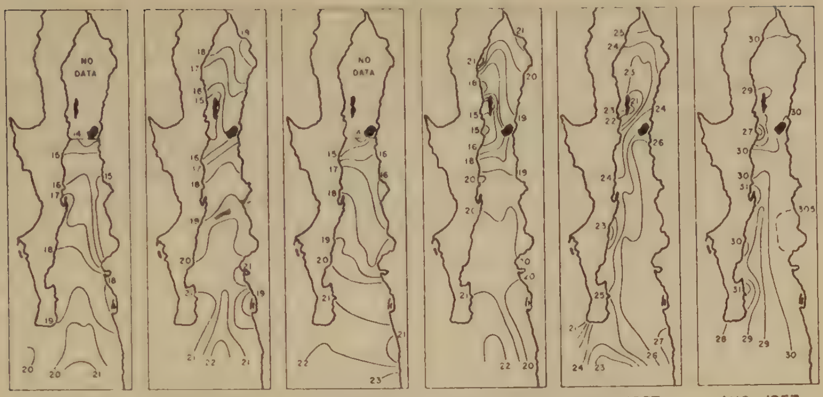
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Figure 2. Horizontal distribution of temperature (°C) at 10 m.

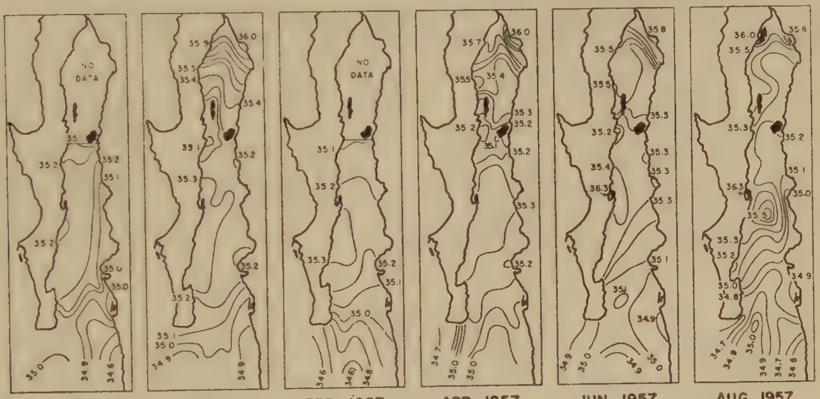
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Figure 3. Horizontal distribution of salinity (‰) at 10 m.

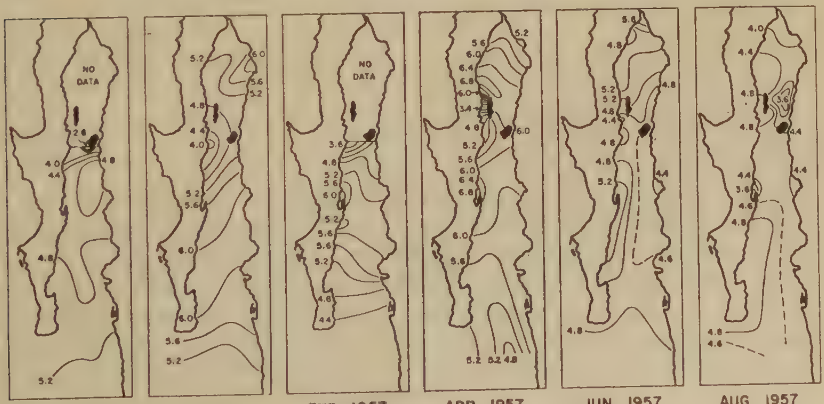
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Figure 4. Horizontal distribution of oxygen (ml/1) at 10 m.

characteristic of conditions offshore. The salinity increases from the Gulf entrance to the mouth of Río Colorado. The latter has no influence upon salinity since runoff is negligible. The lowest salinities are found off river mouths in the southeastern part of the Gulf during the rainy season (July–October) whereas the highest salinities occur in shallow protected bays where evaporation is strong; such areas are Bahía Concepción, Bahía San Felipe and Bahía Adair. The average salinity of the upper 200 m shows almost no seasonal variation.

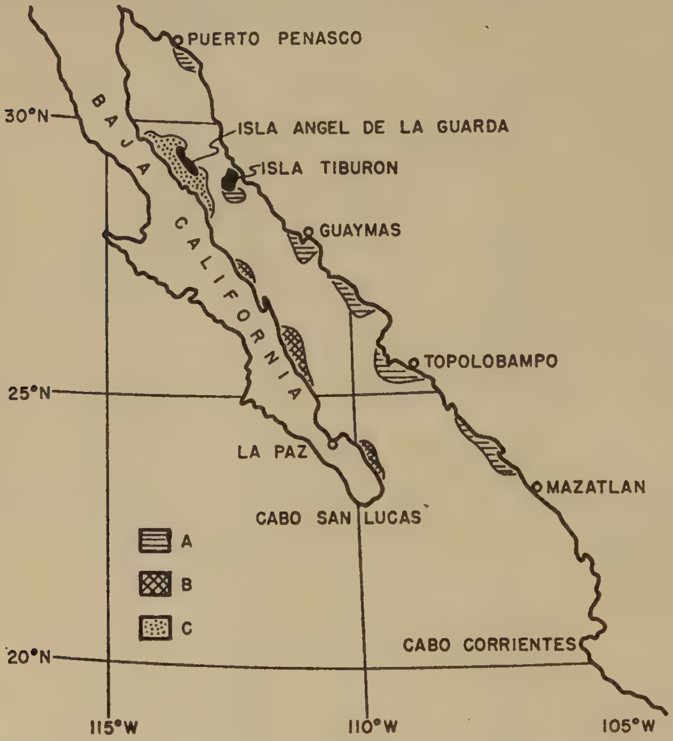
PUERTO PENASCO
30°N
BAJA CALIFORNIA
ISLA ANGEL DE LA GUARDA
ISLA TIBURON
GUAYMAS
TOPOLOBAMPO
25°N
LA PAZ
MAZATLAN
CABO SAN LUCAS
▤ A
▩ B
▨ C
CABO CORRIENTES
20°N
115°W
110°W
105°W

Figure 5. Upwelling areas: a) with northwesterly winds. b) with southeasterly winds. Area c is characterized by strong tidal mixing.

There is some variation of dissolved oxygen with season (Fig. 4). From the solubility of oxygen in sea water one would expect to find the highest concentrations in winter and the lowest in summer, but actually the highest concentrations occur in spring, indicating that biological activity is also important. The surface waters are generally saturated with respect to oxygen, deviations of more than 15% from the saturation value occurring only rarely. A notable exception is found in the vicinity of Isla Tiburón and Isla Angel de la Guarda where undersaturation frequently occurs. Production of oxygen by phytoplankton during the "blooming" season occasionally leads to strong oversaturation.

Upwelling plays an important role. With northwesterly winds upwelling occurs along the east coast and with southeasterly winds along the west coast (Fig. 5). The upwelling areas are mostly found in wind lee of capes, points and islands. The upwelled water is of low temperature, and it is usually of low salinity except along the west coast. Here upwelling frequently leads to higher salinities due to the presence of an intermediate salinity maximum at a depth of about 50 m originating at the northern end of the Gulf. There is no obvious relation between oxygen concentration and upwelling.

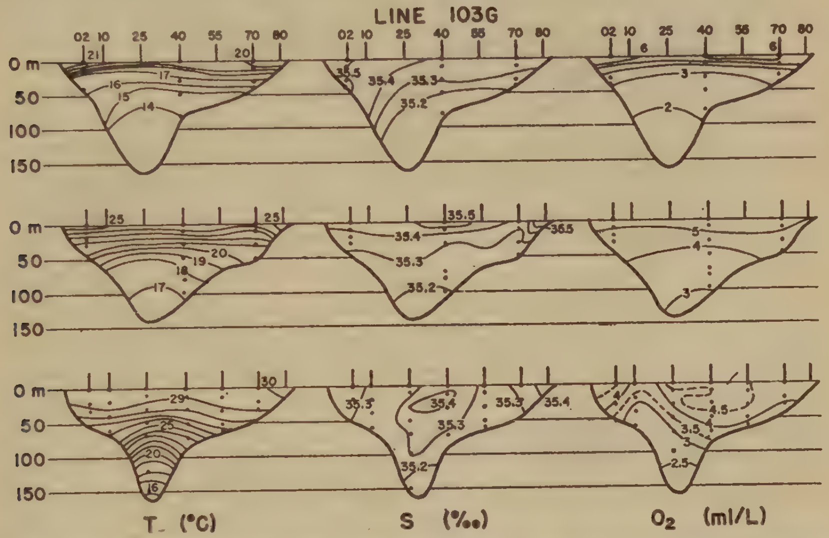

Figure 6. Distribution of temperature, salinity and oxygen in vertical section across the northern part of the Gulf for April, June, and August 1957 in descending order.

Northern Part of Gulf. This region, between Río Colorado and Isla Tiburón, lies in an arid environment which is characterized by large annual temperature ranges and strong evaporation. There is little precipitation (less than 100 mm/year) and runoff is negligible. Winds are predominantly northerly in winter and southerly in summer. The average depth is quite shallow, being about 200 m. An exception is the 1000 m deep trench between Baja California and the islands of Angel de la Guarda and San Lorenzo which is isolated from the rest of the Gulf below 250 m.

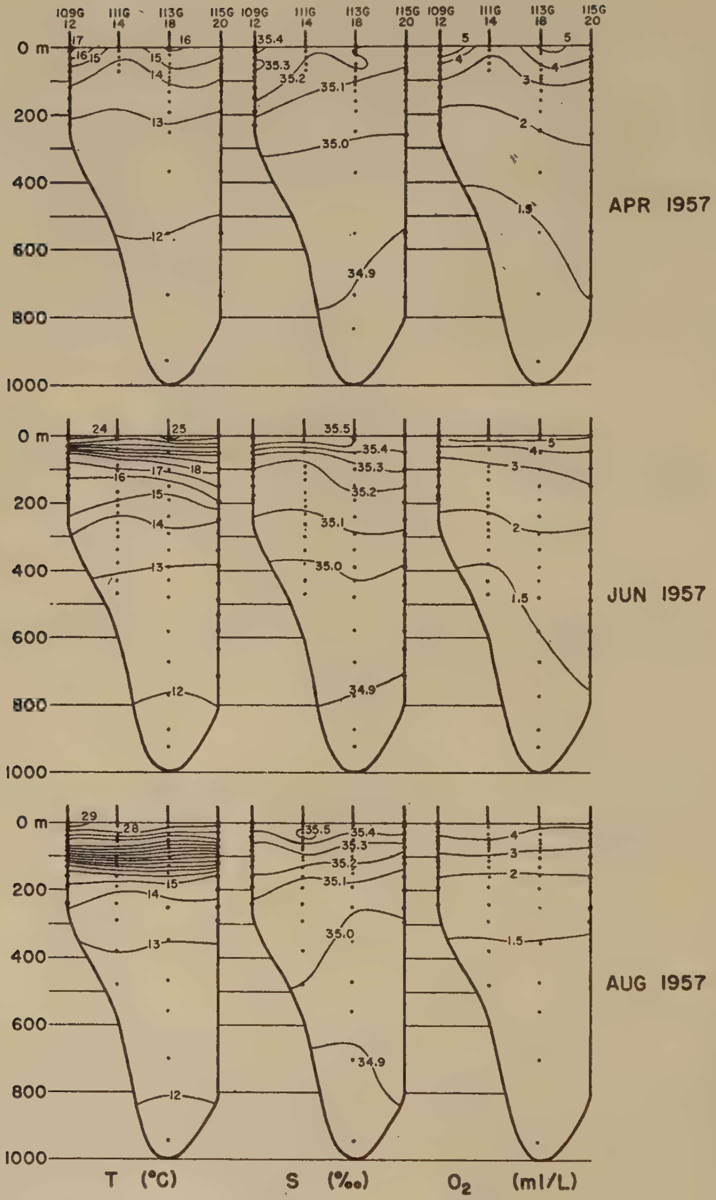

Figure 7. Distribution of temperature, salinity and oxygen in a vertical section along Ballenas Trench.

The distribution of temperature, salinity and oxygen with depth is shown in Fig. 6. Strong temperature gradients between surface and bottom are found during summer months owing to intense solar heating and lack of mixing. Winter conditions have not been thoroughly investigated, but records made at Puerto Peñasco seem to indicate that the water may be almost isothermal (14 C). Salinities, except near the coast, vary between rather narrow limits and are mostly 35.2–35.5‰.

Unusual conditions prevail in the deep trench. Surface temperatures are generally lower here than elsewhere. At depths, temperature, salinity and oxygen (Fig. 7) are much higher than in any other place at that depth. At 1000 m the temperature difference inside and outside the trench is 6°C, the salinity difference 0.4‰, and the oxygen difference 1 ml/L. These features are indicative of intensive mixing which can be attributed to strong tidal currents found there.

Central Part of Gulf. This region between Topolobampo and Isla Tiburón is in a less arid environment than that to the north. Precipitation occurs during late summer months, with the east coast receiving about twice as much as the west coast. Runoff is very slight. The depths are large and there is open communication with the ocean. Winds blow predominantly from the north during winter and from the south during summer.

The distribution of temperature, salinity and oxygen in a vertical cross-section from Santa Rosalía to Cuaymas is shown in Figs. 8 and 9. Below the thermocline the water is the same as in the Equatorial Pacific (Sverdrup, 1941). It is characterized by a salinity minimum (34.50–34.55‰) between 600 and 1000 m and an oxygen minimum (0.1–0.2 ml/L) between 400 and 800 m. The depth at which these minima occur in the gulf is somewhat less than that in the Equatorial Pacific.

Above the Equatorial Pacific water lies a water mass which is distinguished by its higher salinities and which may be called "Gulf water"; this can be looked upon as equatorial water which has been transformed at the surface by evaporation. The salinity and oxygen distributions in the upper layers are very complicated and dependent upon season. Warm temperatures in winter are slightly colder along the east than along the west coast; in summer the opposite occurs. This phenomenon can be ascribed to upwelling. In late summer there appears to be, from consideration of continuity and the presence of salinity tongues, a northward flow of low salinity water along the east coast and a southward flow of high salinity water along the west coast, both occurring at subsurface depths of about 50 m.

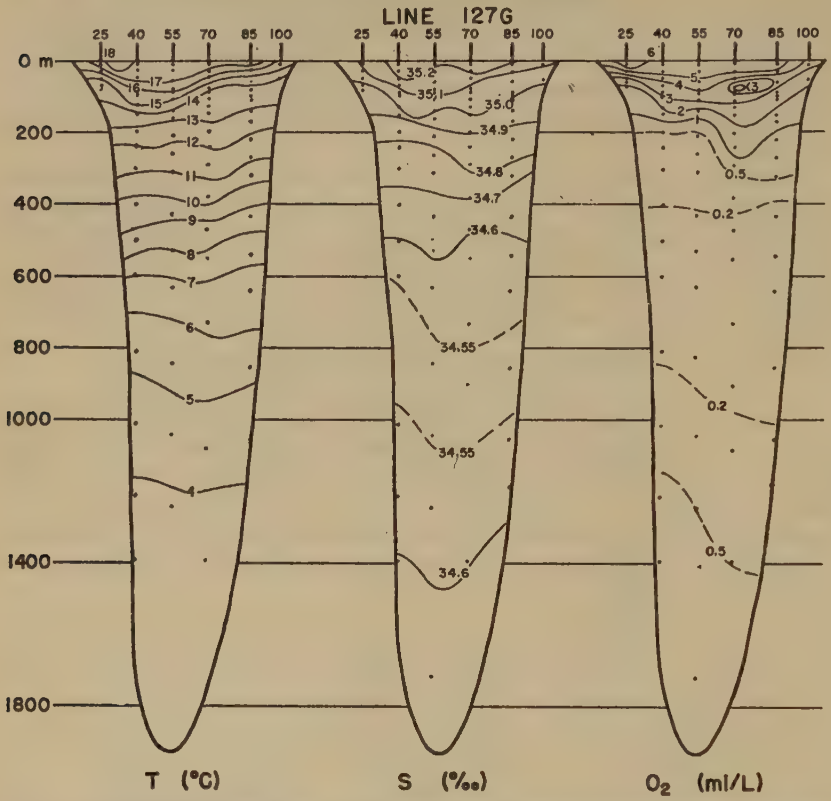

Figure 8. Distribution of temperature, salinity and oxygen in a vertical section across the central part of the Gulf for February 1957.

Southern Part of Gulf. The region between Topolobampo and Cabo Corrientes lies in a moderatley humid environment. Annual precipitation, occurring mostly in late summer and fall, varies between 500 and 1000 mm/year, with less rainfall in the northern part of this region than in the south. During the rainy season there is considerable runoff. Winds are predominantly northerly in winter and southerly in summer. The southern boundary of the Gulf is not well defined, but for oceanographic considerations it can be taken from Cabo San Lucas to Cabo Corrientes. The depths in this part of the Gulf are great, frequently exceeding 3000 m.

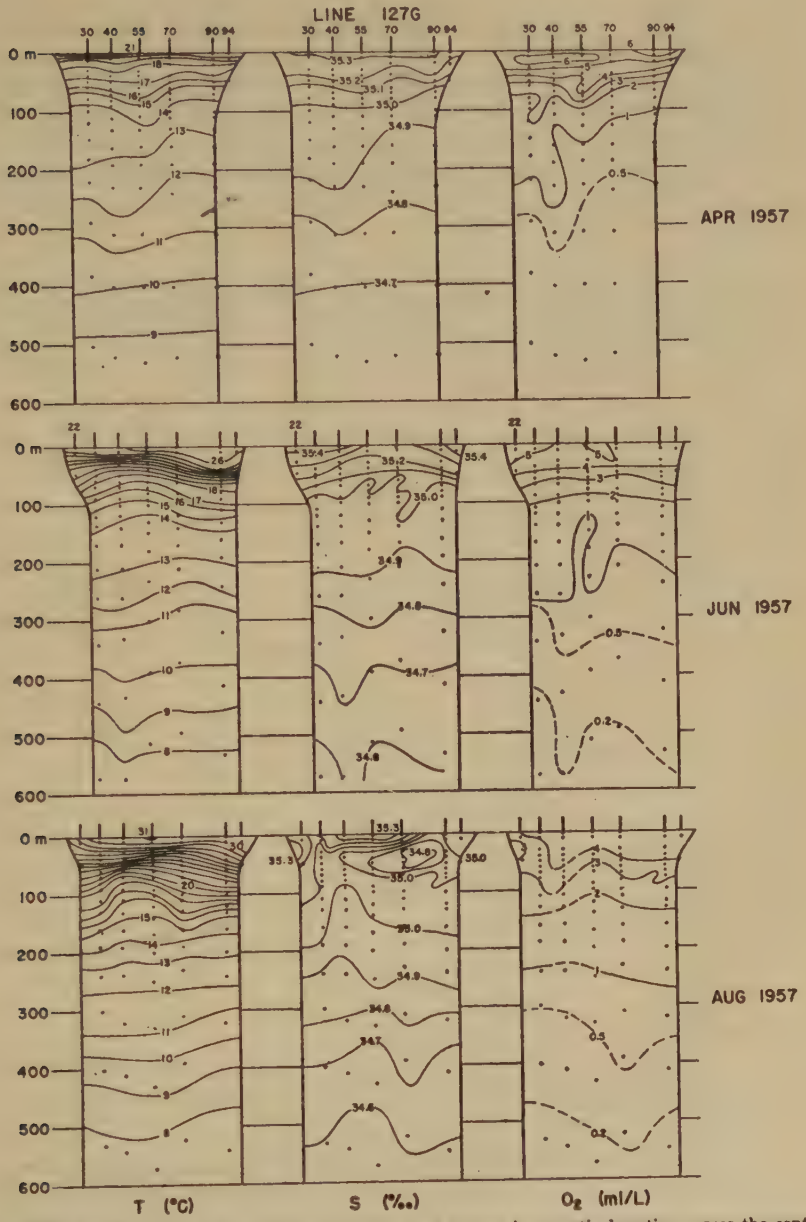

Figure 9. Distribution of temperature, salinity and oxygen in a vertical section across the central part of the Gulf.

Compared to the deep water in the central Gulf (Figs. 8, 9), the deep-water salinity and oxygen minima in this region are more pronounced. Oxygen concentrations in the southern Gulf fall below 0.1 ml/L, which has not been observed further to the north. At great depths conditions are rather uniform, so that no differences are observed between the central and southern parts. No important changes between the 1939 cruise (Sverdrup, 1941) and the 1957 cruise have been found in the deep water of the Gulf.

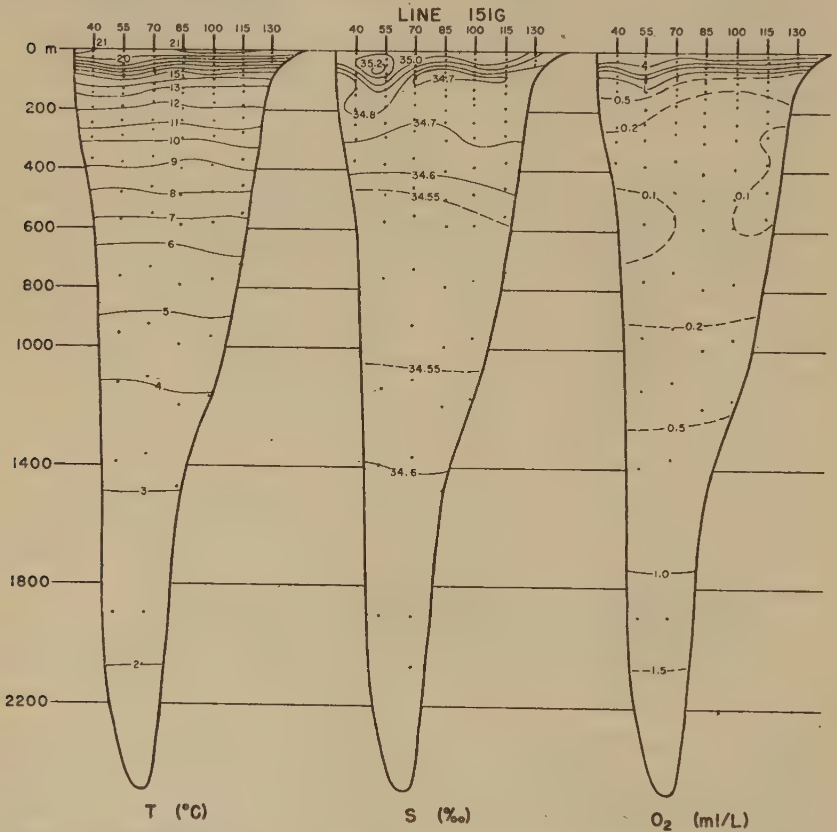

Figure 10. Distribution of temperature, salinity and oxygen in a vertical section across the southern part of the Gulf for February 1957.

In the upper 200 m the distribution of salinity and oxygen is complicated (Figs. 10, 11, 12) because of three distinct water masses: Gulf water, California Current water, and water from the eastern Tropical Pacific. The first is characterized by relatively high temperature and

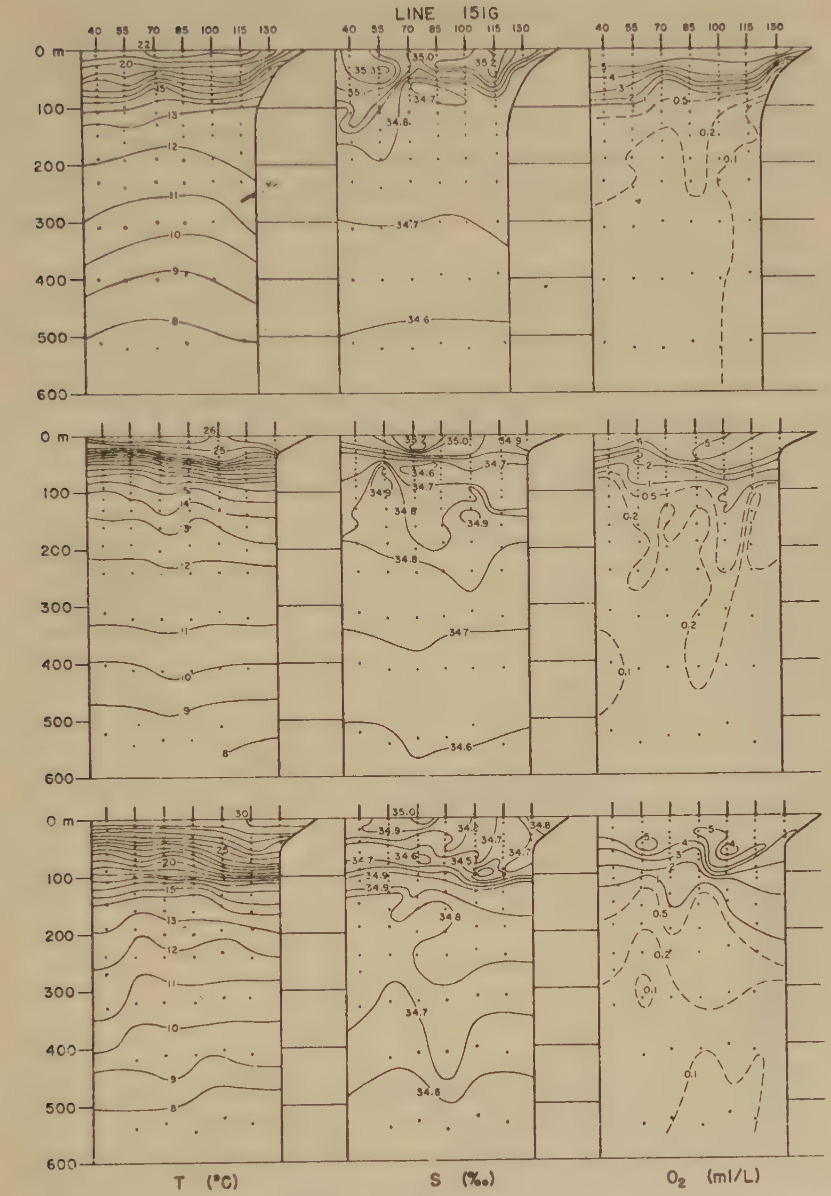

Figure 11. Distribution of temperature, salinity and oxygen in a vertical section across the southern part of the Gulf for April, June and August 1957 in descending order.

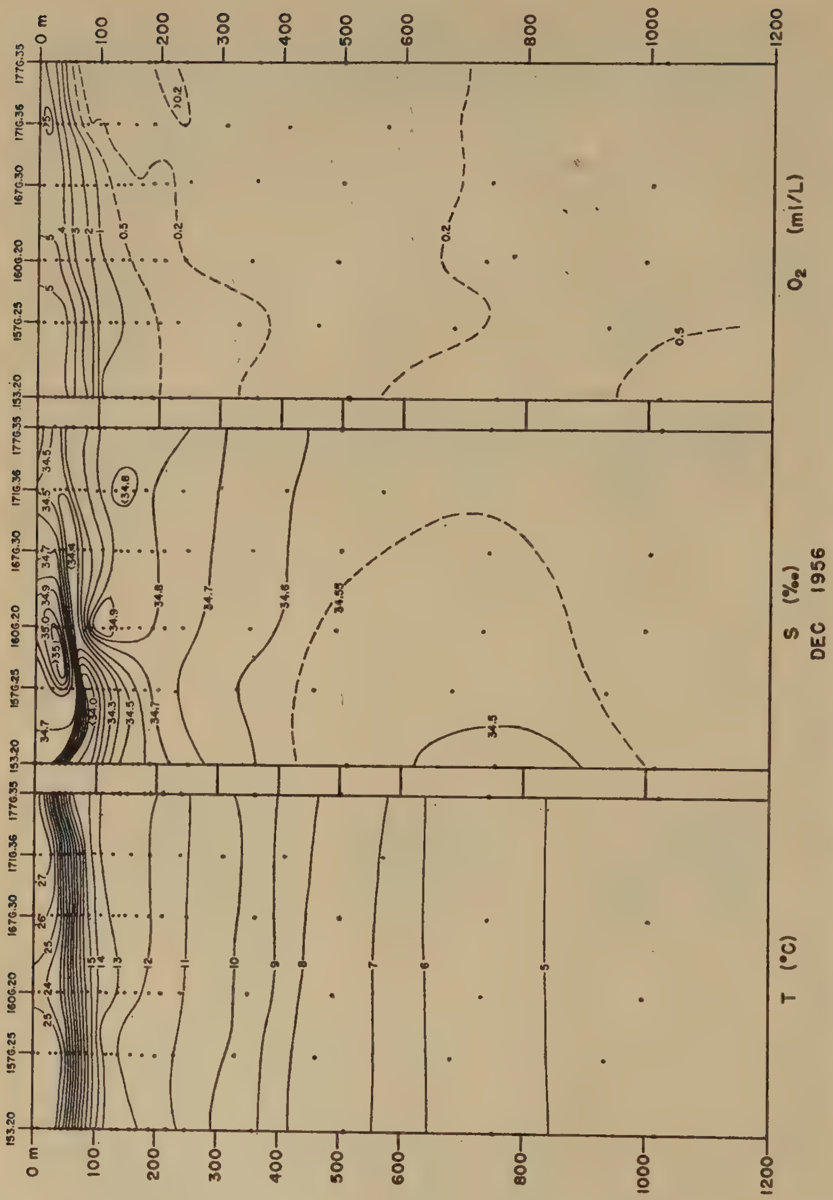

Figure 12. Distribution of temperature, salinity and oxygen in a vertical section from Cabo San Lucas to Cabo Corrientes.

salinity, the second by low temperature and salinity, and the latter by high temperature and relatively low salinity. Where these water masses meet, very sharp gradients are found. This is nearly always the case in the vicinity of Cabo San Lucas and frequently near Cabo Corrientes. The salinity distribution indicates that outflow of Gulf water seems to occur along the Baja California coast, often at depths around 50 m, and that inflow occurs mostly along the east coast and is concentrated around 100 m.

Water Balance in the Gulf. The rate of exchange of water between the Gulf and the Pacific Ocean can be estimated either by applying the geostrophic law to a hydrographic section across the mouth of the Gulf or by salt budget considerations.

The first method was applied along section 151G for the four 1957 cruises, utilizing the 500 m dynamics between adjacent stations. The region of inflowing water was computed separately from the region of outflowing water, and the totals for each, Q_i and Q_o, are tabulated in the first two lines in Table III. Exchange of water other than through the mouth of the Gulf is negligible; therefore, inflow should almost exactly balance outflow (for geostrophic flow, which represents a time average over a period of the order of a pendulum day). Otherwise, ridiculous changes in sea level would soon occur in the Gulf. The discrepancy between inflow and outflow can be ascribed to four principal defects: (1) any flow below 500 m is not accounted for; (2) dynamics based on a 500 m reference surface are in error if there is motion below; (3) there may be transients in the density field that are not geostrophically balanced; (4) the Gulf's mouth is not completely spanned by the end stations. With regard to (1) and (2), the density variation needed between 500 and 1000 m to completely balance inflow and outflow is small and could likely occur. The average salinity of the inflowing and outflowing water is defined by the relation

$$\overline{S} = \frac{\int \rho v S dx\, dz}{\int \rho v dx\, dz}, \tag{1}$$

where v is the geostrophic velocity component normal to the section; the integration over the area of the section is confined to the region of inflowing (or outflowing) water. In making the computation, salinity and dynamic height values were interpolated linearly between stations. For three of the cruises, the outflowing water was more saline than the inflowing, but the opposite is indicated for the June cruise. Of course, this computation is subject to all the uncertainties present in the geostrophic computation.

To apply salt budget considerations, let Q_i, Q_0, E, P and R represent inflow, outflow, evaporation, precipitation and runoff, respectively, each expressed as mass of water per unit time. Then conservation of water and salt can be expressed as follows:

$$\begin{aligned} Q_i &= (E - P - R)\overline{S}_0/(\overline{S}_0 - \overline{S}_i), \\ Q_0 &= (E - P - R)\overline{S}_i/(\overline{S}_0 - \overline{S}_i), \end{aligned} \tag{2}$$

where $\overline{S}_i$ and $\overline{S}_0$ are the mean salinities of the inflowing and outflowing water, defined by (1). These relationships need not be fulfilled at any given instant of time since there may be short-term variations in the total quantity of water and salt within the Gulf. The pertinent question to consider in such statements of conservation is "For how long a time can the substance under consideration accumulate (or be lost) at a reasonable rate until the concentration reaches an absurd value?" For conservation of water mass, this time is of the order of a seiche period of the gravest mode, or about a day. For salt, however, a time of the order of six months is needed for the average salinity in the upper 200 m to change measurably due to uncompensated evaporation. Therefore, all quantities in equations (2) must represent time averages of approximately six months, and we shall apply (2) not to each of the four 1957 cruises but only to their average.

Evaporation, E, can be estimated from the relationship

$$E = KA\rho W\Delta e, \tag{3}$$

where A is the surface area of the Gulf (cm²), ρ the density of fresh water (g/cm³), Δe the vapor pressure difference (mb) between the sea surface and the air above it, W the wind velocity (m/sec), and K a factor of proportionality, here taken as 0.011 (for details, see Sverdrup, 1951). The estimates of E, P, R in Table III are based on data collected during the cruises and on past weather data at the corresponding time of year (Servicio Meteorológico Mexicano, 1937).

These values can now be used to estimate the water exchange rate according to (2), provided that a suitable estimate of the average salinities $\overline{S}_i$ and $\overline{S}_0$ can be made. An objective way is to use the values from lines 3 and 4, derived from the geostrophic estimate. The resultant estimate of in- and out-flow is given in the last two lines of Table III for the average of the four 1957 cruises. This estimate, of course, depends rather critically on the salinity difference between the in- and out-flowing water, which, according to the geostrophic estimate, is 0.04‰. Actual examination of the salinity profiles across line 151G

TABLE III.

			February	April	June	August	Average
geostrophic estimate	Q_i	(10^{12} g/sec)	0.9	1.6	2.2	2.8	1.9
	Q_0	(10^{12} g/sec)	1.2	1.5	1.2	1.6	1.4
	S_i	(‰)	34.75	34.78	34.84	34.75	34.78
	S_0	(‰)	34.82	34.91	34.76	34.78	34.82
	E	(10^9 g/sec)	3.6	1.7	7.7	7.2	5.0
	P	(10^9 g/sec)	0.4	0.1	0.2	2.2	0.7
	R	(10^9 g/sec)	0.2	0.2	0.3	0.6	0.3
conservation of salt estimate	Q_i	(10^{12} g/sec)	—	—	—	—	3.5
	Q_0	(10^{12} g/sec)	—	—	—	—	3.5

suggests that a salinity difference 10 times greater might be more likely, and this would lead to a water exchange rate only $^1/_{10}$ as great (Roden, 1958).

It is seen that evaporation exceeds precipitation and runoff in all months examined. Precipitation amounts to less than 10% of evaporation during the first half of the year, but during the rainy season, which lasts from July to October, precipitation increases in importance. There is little runoff from the Río Colorado (Valenzuela, personal communication) and the other rivers do not discharge much water into the Gulf except during the rainy season.

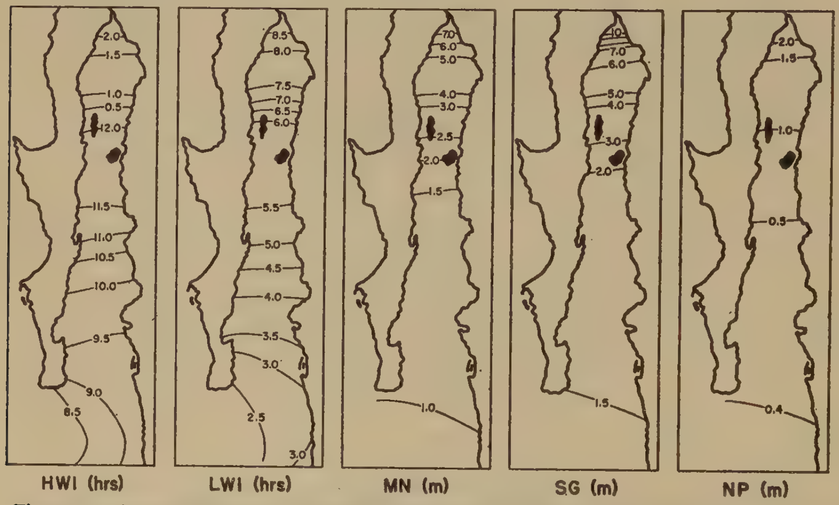

Figure 13. Tides in the Gulf of California: HWI-high water interval. LWI-low water interval. Mn mean range. Sg-spring range. Np-neap range. Time in hours; ranges in meters.

Tides. Tide observations have been recorded from very few locations in the Gulf. Generally the tide appears to be of the mixed type, with large diurnal inequalities which may predominate in some parts of the central Gulf. The composite tidal range increases gradually from the Gulf entrance to Isla Tiburón, and then rapidly toward the mouth of the Río Colorado. In this vicinity it is very large, exceeding 10 m during the spring tides. The tidal wave continues into the Rio Colorado in the form of a bore. Fig. 13 (after U. S. Coast and Geodetic Survey, 1915) shows the observed tidal ranges and high and low water intervals.

Whether the tidal oscillation within the Gulf behaves predominantly like a standing wave or like a progressive wave travelling northward depends on the amount of tidal power that is dissipated inside the Gulf.

With relatively little dissipation, most of the incoming energy would be reflected from the head of the Gulf, so that the result would appear as a standing wave. The high water interval would change rather abruptly at a node by half a tidal period. On the other hand, with relatively high dissipation, the tidal wave behaves more like a progressive wave, and we would expect the high water interval to vary smoothly with distance from the mouth of the Gulf. Evidence indicates that the time of high water gets progressively later with distance up the Gulf, with high water occurring about 5.5 hours later at its head than at its mouth; this is about the time needed for a free progressive shallow-water wave to traverse the entire length of the Gulf. But 5.5 hours is also approximately half a semidiurnal tidal period, which is the lag that would occur if the tidal wave were a pure standing oscillation. Evidence is hardly good enough to distinguish between the two alternatives.

If we neglect the small input of tidal energy by the direct action of sun and moon on the body of water in the Gulf, then the total amount of tidal power entering through the mouth is

$$P = \rho g \int h v \eta \, dx, \tag{4}$$

where h is mean water depth, η the surface elevation, v the component of orbital velocity northward along the Gulf axis, ρ the water density, and x the distance across the Gulf entrance. To get an estimate of the tidal power dissipated within the Gulf, let us assume that an ingoing progressive tidal wave is entirely dissipated. Then η and v will be in phase, and (4) gives $P = 0.4 \times 10^{18}$ ergs/sec, averaged over a tidal cycle.[2]

Let us now see if it is at all likely that such a large amount of power could be dissipated by friction of tidal currents along the bottom. The stress exerted by a tidal stream on the bottom is proportional to the square of the speed, the velocity being roughly constant from top to bottom (Taylor, 1919). The power dissipated per unit area of bottom is then proportional to the cube of the current speed, according to

$$P/A = K\,V^3, \tag{5}$$

where K is a numerical constant having a value near 0.0018. In Ballenas Trench (between Isla Angel de la Guarda and Baja California) and off the mouth of the Río Colorado, speeds of more than 3 m/sec (6 knots) have been reported (U. S. Hydrographic Office, 1951). If currents of such magnitude occurred continuously throughout a 1000 km² area, then it would dissipate the same amount of power, 0.4 × 10^{18} ergs/sec. The area required does not seem excessively large, and so the computed amount of tidal power dissipated seems reasonable. If true, the Gulf of California would supply 3% of the tidal dissipation needed to account for the observed secular acceleration of the moon.

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[2] If the tidal oscillation consists of two progressive waves, one entering and one leaving, it is possible that an even greater dissipation occurs for a given tide range at the entrance provided the phase relations are such that some cancellation between the two waves occurs (Taylor, 1919).

From the free standing-wave viewpoint (no dissipation), the semidiurnal tide has a node in the central region of the Gulf, where observations show the diurnal contribution to be relatively important. The high range observed off the mouth of the Río Colorado is due to narrowing and shoaling of the Gulf.

As a result of the high tidal range and the complicated bottom topography, tidal currents are strong, especially in narrow channels and in the vicinity of Río Colorado. The mixing effected by these strong tidal currents may have important biological consequences.

Variations of Surface Slope Across the Gulf Entrance. These variations have been studied from sea level and atmospheric pressure records made in Mazatlán, Sin., and La Paz, B.C. Monthly average values of sea level for these two stations (from 1953 into 1957) are shown in Fig. 14 (A and B); a mean annual cycle, determined from three years of record, is shown in Fig. 15. It is seen that there is a prominent seasonal cycle reaching its maximum in summer and its minimum in winter, with Mazatlán leading slightly in phase over La Paz. The range of the seasonal oscillation is from 20 to 40 cm and is noticably larger in Mazatlán than in La Paz. The double maxima which are seen in three out of four annual cycles at Mazatlán may be a characteristic local phenomenon.

In the sea, the pressure gradient at the surface is composed of two parts: (1) that arising from the gradient of the surface elevation, and (2) the atmospheric pressure gradient. Note that one millibar is equivalent to approximately one centimeter of sea water pressure. The sum of the sea-surface elevation and the atmospheric pressure, expressed as equivalent height of a column of sea water, has been referred to as *corrected sea level* (Groves, 1957). The corrected sea level for Mazatlán and La Paz was computed from the monthly mean pressures at these two places (corrected to sea level) and the monthly sea level means. The difference of corrected sea level, Mazatlán minus La Paz, is shown in Figs. 14 (C) and 15 (C). This plot can be interpreted to mean the horizontal pressure difference in centimeters of sea water between the two stations. The time variations of it are proportional to variations in the inflowing geostrophic current. The datum is arbitrary, since the height of mean sea level at La Paz is unknown relative to mean sea level at Mazatlán because the two places have never been levelled in together. Consequently, the method gives only variations of the mean inflowing surface current and not the surface current itself.

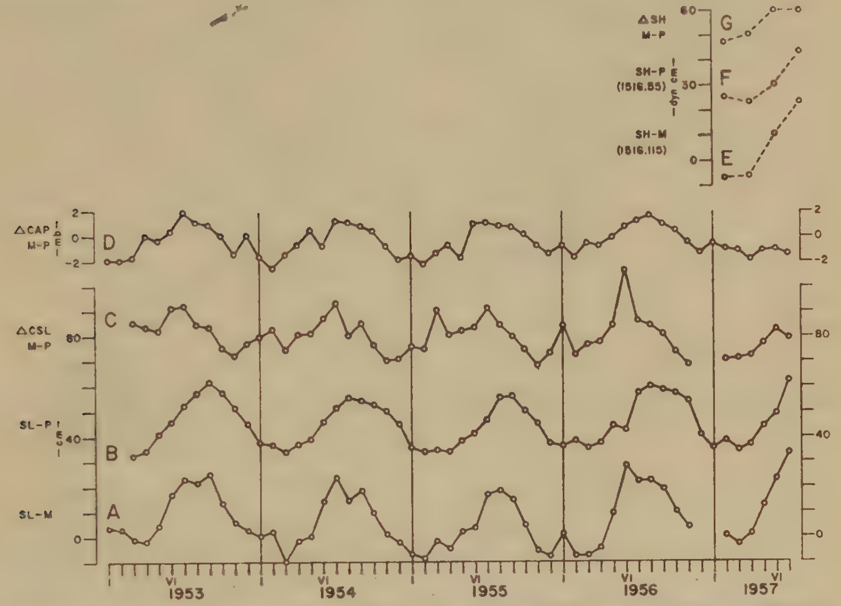

Figure 14. A—monthly mean sea level at Mazatlán; B—monthly mean sea level at La Paz; C—monthly mean difference in corrected mean sea level, Mazatlán minus La Paz; D—monthly mean difference in atmospheric pressure corrected to sea level, Mazatlán minus La Paz; E and F—steric height at stations 151G.115 and 151G.55, respectively; G—difference in steric height, station 151G.115 minus station 151G.55. Curves A, B, C, E, F, G, are plotted relative to arbitrary datum.

Mean monthly differences in atmospheric pressure (corrected to sea level), Mazatlán minus La Paz, are illustrated in Figs. 14 (D) and 15 (D). The difference is proportional to the southerly component of geostrophic wind across the entrance to the Gulf. The similarity between curves C and D in Figs. 14 and 15 might be interpreted to mean that a southerly wind across the Gulf entrance is conducive to inflow of surface waters. If it is assumed that the inflowing surface current is proportional to the surface wind from the south, the constant of proportionality can be determined by the least square method. The result is that the ratio between inflowing current and southerly wind at the sea surface is 0.0054. This value does not disagree radically with the 2% value used by navigators. The discrepancy

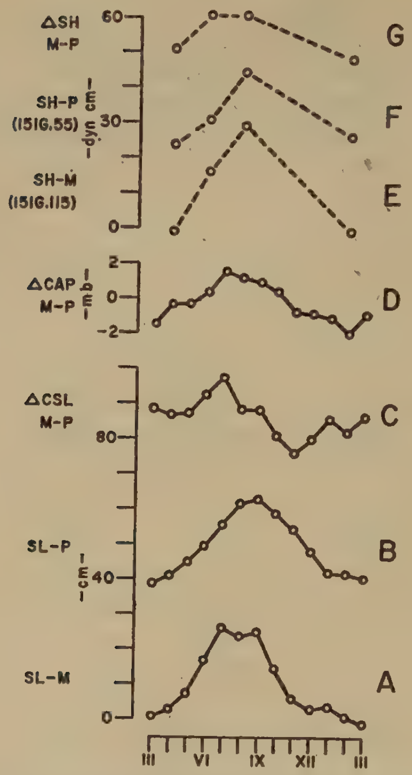

Figure 15. Curves A, B, C, D, represent an average annual cycle of the corresponding curves in figure 14. Curves E, F, G represent single observations only.

should not be taken too seriously in view of the fact that water is blown into or out of a confined basin in contrast to open ocean conditions.

Variations in *steric height* (Pattullo *et al.*, 1955) or dynamic height reflect variations in the sea surface elevation due exclusively to changes in density of sea water in a vertical column. Steric height variations across the Gulf entrance, as obtained from CCOFI stations 151G.115 (close to Mazatlán) and 151G.55 (close to La Paz), are shown in Figs. 14 (E, F) and 15 (E, F). The difference in steric height, Mazatlán minus La Paz, is shown in Figs. 14 (G) and 15 (G). Note: data for curves E, F and G represent monthly isolated instantaneous measurements, not monthly averages, and in Fig. 5 these curves are compared with other curves based on a mean annual cycle from three years of continuous data. Consequently curves A through D deserve much more confidence than do E, F, and G. In comparing curve E with A, F with B, G with C, one can say that there is no contradiction in the supposition that the observed sea level variations at Mazatlán and La Paz are related primarily to changes in density of sea water.

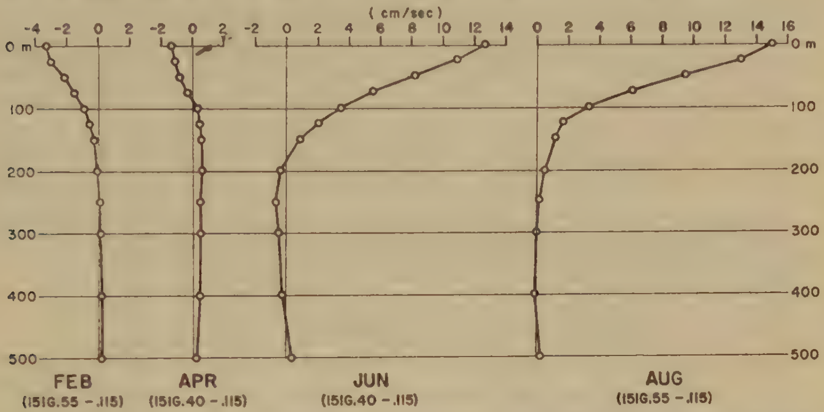

Figure 16. Horizontally averaged geostrophic current as function of depth. The plots for February and August are averaged between stations 151G.55 and 151G.115, while the plots for April and June are averaged between stations 151G.40 and 151G.115.

The horizontally averaged inflow, plotted against depth, is shown in Fig. 16. For April and June the inflow was determined from CCOFI stations 151G.115 and 151G.40 and for February and August from stations 151G.115 and 151G.55, since station 151G.40 was not occupied during the last mentioned months. It is seen that, during June and August, surface inflow is quite large and that a compensating current below 200 m is evident. February and April indicate just the opposite, with surface outflow and subsurface inflow; however, the exchange is much weaker than in summer. Exact compensation (a mean value of precisely zero, if averaged vertically) is not obtained for reasons discussed in the section on Water Balance.

In conclusion the following points seem to be borne out from observations of sea level, atmospheric pressure and density of sea water at the entrance to the Gulf of California:

1. A southerly surface wind generates an inflowing surface current.
2. The velocity ratio between the inflowing surface current and the southerly wind is about 0.005.
3. Geostrophic flow at the surface is compensated by a reverse flow at depths.

Conclusions. Recent oceanographic investigations have shown that the water mass encountered in the Gulf is characteristic of Equatorial Pacific water. At the surface this water is slightly modified by extensive evaporation which increases its salinity. Seasonal temperature variations observed in the upper layers are large in the central and northern parts and moderately large in the southern part. Seasonal salinity variations are quite small. The seasonal variation of oxygen shows a maximum in spring, indicating that biological activity is of importance. The rather unusual hydrographic conditions in Ballenas Trench, between Isla Angel de la Guarda and Baja California, were attributed to isolation of the Trench and to mixing by strong tidal currents. No changes in the distribution of properties were observed in the deeper part of the Gulf since the last survey in 1939. An estimate of the water budget shows that exchange of water with the Pacific Ocean is of the order of 10^6 m^3/sec, and evaporation is about 5 × 10^3 m^3/sec. Runoff and precipitation are negligible. Comparison of sea level and atmospheric pressure records at La Paz, B.C. and Mazatlán, Sin. with hydrographic observations suggests that variations in sea level are primarily steric. At the surface the currents follow the winds, while at depths a compensating current opposite to the wind direction is generally indicated. The tide in the Gulf is of the mixed type with large diurnal inequalities. A large part of the tidal energy may be dissipated in the northern part of the Gulf, the tide appearing essentially as a progressive wave. The high tidal ranges in the northern part are due to narrowing and shoaling of the Gulf.

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REFERENCES

GROVES, G. W.

1957. Day to day variation of sea level. Meteorol. Monogr., *2* (10): 32–45. June.

OCEANIC OBSERVATIONS OF THE PACIFIC.

1956, 1957. University of California Press. Los Angeles and Berkeley.

PATULLO, JUNE, W. H. MUNK, ROGER REVELLE, AND ELIZABETH STRONG

1955. The seasonal variation in sea level. J. mar. Res., *14* (1): 88–155.

RODEN, G. I.

1958. Oceanographic and meteorological aspects of the Gulf of California. Pacif. Sci., *12* (1): 21–45.

SERVICIO METEOROLOGICO MEXICANO.

1937, 1938. Bol. anu., Tacubaya, D.F.

SVERDRUP, H. U.

1941. The Gulf of California: Preliminary discussions of the cruise of the E. W. SCRIPPS in February and March, 1939. Proc. 6th Pac. Sci. Congr. Calif., *3:* 161–166.

1951. Evaporation from the oceans. Amer. met. Soc. Compendium of Meteorology: 1071–1081.

TAYLOR, G. I.

1919. Tidal friction in the Irish Sea. Philos. Trans., (A) *220:* 1–33.

TANNER, F. L.

1888. Report on investigations of the U.S. Fish Commission steamer ALBATROSS for the year ending June 20, 1889. Rep. U.S. Comm. Fish. (1888): 395–512.

U.S. COAST AND GEODETIC SURVEY.

1915. General Tide Tables for the year 1916. Washington, D. C.

1954. Density of sea water at tide stations. Spec. Publ. 281. Washington, D. C.

1956. Surface water temperatures at tide stations: Spec. Publ. 280. Washington, D. C.

U.S. HYDROGRAPHIC OFFICE

1951. Sailing Directions (H.O. 84) West Coast of Mexico and Central America. Washington, D. C.

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ON THE HEAT AND SALT BALANCE OF THE CALIFORNIA CURRENT REGION

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ON THE HEAT AND SALT BALANCE OF THE CALIFORNIA CURRENT REGION[1]

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ABSTRACT

The average monthly variation of the heat and salt balance of the upper 200 m is investigated for eight areas of the Pacific Ocean off California and Baja California. Accuracy of the method and of the nonseasonal variations of the balance is estimated. It is shown that observed heat changes are princiaplly due to radiation and advection, the heat exchange with the atmosphere being rather small and constant. Evaluation of the advection term by two independent methods shows only little agreement. Observed salt changes seem to be related principally to advection and to a lesser degree to the excess of evaporation over precipitation.

Introduction. In recent years increased effort has been directed toward a better understanding and a more accurate evaluation of the different terms involved in calculating the heat balance. Aspects of radiation were investigated by Anderson (1952), Berliand (1952), Black (1956), Burdecki (1958) and Budyko (1956). The heat exchange of the atmosphere was dealt with by Budyko (1956), Jacobs (1951) and Sverdrup (1951). The monthly heat balance of the earth's surface was investigated by Budyko (1955) and of the oceans by Pattullo (1957). On a regional scale, Koizumi (1956) and Tabata (1958) have studied the heat balance off Japan and off the west coast of Canada, respectively.

In the region of the California Current almost no work has been done on the heat balance, mainly because the necessary data were lacking. In the past ten years, however, a great amount of information has been gathered through regular hydrographic cruises. Thus, for the first time it becomes possible to investigate the relative importance of rates of radiation, heat exchange with the atmosphere, local heating, and advection.

Radiation can be considered an important factor of the heat balance owing to the small amount of clouds usually found over the California Current region. On the other hand, turbulent heat exchange with the atmosphere will probably play only a minor part in the balance because of the rather low and constant wind velocities and the stable

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stratification of the air. Advection can be expected to be important owing to the presence of the California Current and the frequent occurrence of upwelling. Since cold water is brought into the region, advection represents a loss of heat from the balance point of view.

The change of salt in the California Current region can be expected to be related primarily to advection, because both evaporation and precipitation are small. There is not sufficient runoff to alter the salt balance.

Data. Eight areas bounded by five degree squares of latitude and longitude were selected for the present investigation (Fig. 1). This rather arbitrary selection was necessary because of the limited amount of climatological data available. Air temperatures, sea surface temperatures and cloudiness were obtained from publications of the Imperial Marine Observatory in Kobe, Japan (1911–1938). Wind velocities were procured from the U. S. Hydrographic Office (1956), atmospheric pressures from unpublished records of the U. S. Weather Bureau (1899–1958). Temperatures and salinities in the upper 200 m of the ocean were obtained from cruises made by the Scripps Institution of Oceanography in collaboration with the South Pacific Fishery Investigations of the U. S. Fish and Wildlife Service (Oceanic Observations of the Pacific, in press).

The number of observations taken per month in each square is shown in Table I. Compared to about 400 to 1200 observations of air temperatures, sea surface temperatures, and cloudiness, only 0–250 are available for the average temperature and salinity of the upper 200 m.

Theoretical Considerations

A) HEAT BALANCE. The heat used locally for changing the temperature of a water column can be expressed, according to the equation of the heat balance, as

$$Q_L = Q_r + Q_a + Q_v, \tag{1}$$

where Q_L denotes the rate of local heat change, Q_r the rate of effective radiation, Q_a the rate of exchange of heat with the atmosphere through processes of evaporation, condensation and convection, and Q_v the rate of heat brought into the region by ocean currents and by mixing. The first three terms are calculated from oceanographical and meteorological observations; the advection term is found by difference. The units used in this paper are cal cm^{-2} day^{-1}.

The method of the heat balance requires knowledge of the transmission of solar energy through the atmosphere, of the processes

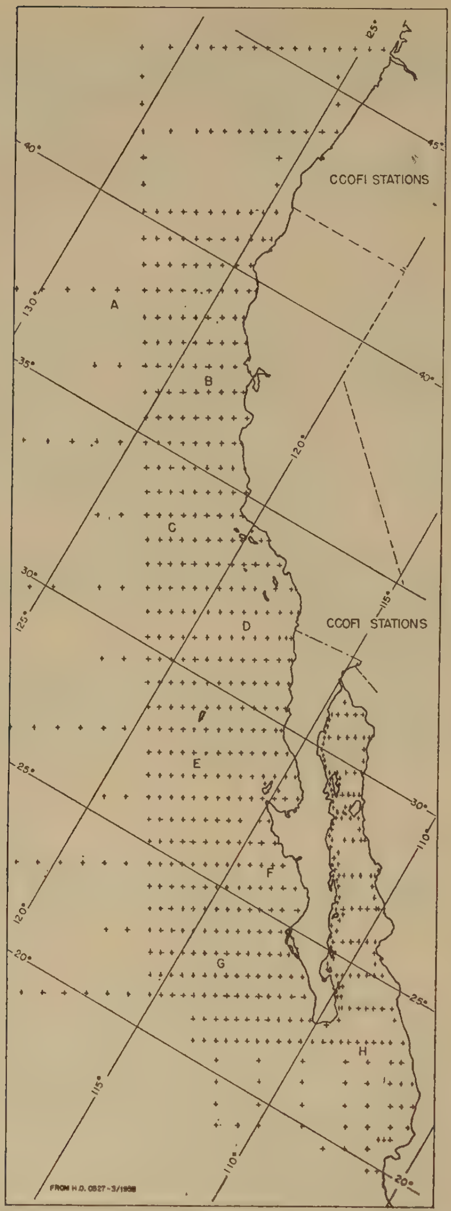
CCOFI STATIONS
CCOFI STATIONS
A
B
C
D
E
F
G
H
45°
40°
35°
30°
25°
20°
130°
125°
120°
115°
110°
FROM H.O. 0527-3/1958

Figure 1. Stations occupied during CCOFI cruises off California and Baja California (dots) and areas used in the present investigations (letters).

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TABLE I. TOTAL NUMBER OF OBSERVATIONS IN EACH FIVE DEGREE SQUARE OF LATITUDE AND LONGITUDE BY MONTHS

Month / Square	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Air temperature, sea surface temperature, cloudiness.												
A	881	952	1046	1056	1127	1246	1216	1340	1097	1136	986	1010
B	724	728	841	945	978	1015	955	1058	948	884	777	789
C	498	451	526	491	490	505	464	575	469	495	498	530
D	696	625	717	711	683	757	678	807	710	665	675	692
E	514	471	518	530	539	530	543	577	565	454	504	508
F	419	378	427	434	422	396	399	456	441	358	417	418
G	546	512	609	562	605	557	590	668	598	499	559	602
H	641	568	633	647	625	608	676	714	647	548	609	658
Average temperature of upper 200 meters.												
A	0	13	16	26	28	35	41	31	22	7	7	2
B	11	9	9	44	43	85	61	54	26	26	22	9
C	60	84	61	181	107	149	106	68	28	60	30	32
D	75	128	80	171	104	129	102	73	59	109	42	75
E	99	155	121	240	147	118	119	66	56	110	44	57
F	31	42	36	58	39	43	35	25	14	32	21	17
G	20	56	34	44	6	46	7	11	19	2	36	26
H	0	21	1	13	0	11	0	11	1	0	1	26
Average salinity of upper 200 meters.												
A	0	13	16	22	24	25	12	10	20	6	4	0
B	0	9	9	35	31	80	37	24	19	19	13	0
C	33	70	43	54	85	127	59	37	18	50	21	25
D	52	110	56	147	77	103	69	51	37	88	23	56
E	64	126	88	202	103	105	85	50	44	46	34	49
F	4	33	26	47	24	30	24	17	10	25	15	15
G	19	53	31	42	4	15	2	10	1	2	36	25
H	0	25	1	21	0	11	0	11	0	0	1	25

(485)

occurring at the boundary between the sea and the atmosphere, and of the conditions in the sea itself. The processes involved are complicated and one is compelled to use many restrictive assumptions when calculating the heat balance.

The rate of local heat change, which can be calculated from a knowledge of the vertical temperature distribution in the sea, is given by the expression

$$Q_L = C_p \cdot \rho \int_0^z \frac{\partial \theta}{\partial t} dz \qquad (2)$$

where C_p is the specific heat of sea water at constant pressure (0.94 cal/g), ρ the mean density of the water column (1.024 g/cm³), θ its temperature (°C), t time, and z the depth at which the seasonal variation of temperature becomes small enough to be neglected. The specific heat and density have been assumed constant, i.e., they are represented by their mean values, because it is permissible to neglect the small variations with temperature and salinity. The depth of no seasonal variation is obtainable from an inspection of temperature records at different levels in the sea; this depth, in the region concerned, lies at about 200 m.

The rate of effective radiation, i.e. the difference between total heat absorbed by the water mass and total back radiation from the sea surface per unit time, can be expressed as follows, according to Budyko (1956),

$$Q_r = Q_o(1 - r)(1 - k'C) + Q_{bo}(1 - k''C^2) + 4s\sigma\theta^3(\theta_{\text{sea}} - \theta_{\text{air}}), \qquad (3)$$

where Q_o is the total incoming short wave radiation with a clear sky, r the amount of radiation reflected, C the cloudiness in tenths of the sky covered, Q_{bo} the effective back radiation with a clear sky, θ the absolute temperature, s the ratio of the radiation from the sea surface to a black body, and σ the Stefan-Bolzmann constant; k' and k'' are factors depending upon latitude. The first term represents incoming radiation, the second term back radiation, and the third term the effect of stability upon back radiation (see below).

Total (direct + diffuse) incoming radiation is frequently measured by pyrheliometers at certain meteorological stations. From time series of such measurements, incoming radiation with a clear sky and with a sky covered by clouds of various amount, height and thickness may be evaluated. Upon combining measurements from many similarly located stations, an average picture of incoming radiation at different latitudes can be obtained. It has been found by Kimball (1928) and Budyko (1956) that the ratio of incoming radiation of a clear to a cloudy day depends linearly upon cloudiness. Kimball's ratio, based upon measurements made in the United States, does not depend on latitude; but Budyko, considering all available stations in the northern hemisphere, found that this ratio decreases toward the poles. In latitudes between 25–45N, agreement between Budyko's and Kimball's ratios is very close. Another attempt to evaluate the ratio was made by Black (1956), but recently his methods have been questioned by Burdecki (1958). Average monthly values of total incoming radiation with a clear sky, as determined by Budyko (1956), are given in Table II; the latitudinal dependence of the ratio of radiation with a clear to a cloudy sky is shown in Table III.

Effective back radiation is the difference between long wave radiation from the sea surface and long wave radiation from the atmosphere. It decreases with increasing humidity and stability of the air and, for the range of humidities commonly observed at sea, it decreases also with increasing temperature (Fig. 2). Berliand (1952) has given the following semiempirical equation from which effective back radiation can be computed:

$$Q_b = -[s\sigma\theta^4 (0.39 - 0.050 \sqrt{e})(1 - k''C^2) + 4S\, \theta^3(\theta_{\text{sea}} - \theta_{\text{air}})], \quad (4)$$

where s is the ratio of the radiation of the sea surface to a black body, σ the Stefan-Bolzmann constant, θ the absolute temperature, e the vapor pressure of air (mb), k'' a constant, and C the cloudiness in tenths.

The first term, which takes into account the effect of temperature, humidity and cloudiness, varies, for the ranges generally found in oceanic regions, between 20 and 200 cal cm^{-2}day^{-1}. The constant k'' has been evaluated by considering also the vertical extent of clouds as well as the height of the cloud base from the surface of the earth; it was found that k'' increased from the equator to the pole (Table III) because of the decrease in cloud base heights in polar regions. The second term considers the effect of stability. Owing to the small sea-air temperature differences observed over the oceans, this term is rather small and varies for the most part only between -20 to $+20$ cal cm^{-2}day^{-1}.

Compared with early methods for evaluating effective back radiation (Asköl f, 1920), Berliand's equation yields results that are about 50% lower than those found previously. A similar discrepancy with early methods was also found by Anderson (1952). An explanation for the disagreement between recent and early results can be sought in the fact that the constant k'' is not the same for all places but varies with latitude, depending upon the vertical dimensions of clouds.

TABLE II. Total incoming radiation with a clear sky in cal cm^{-2} day^{-1} (after Budyko, 1956)

Lat \ *Month*	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Year*
Av.	293	356	486	599	706	733	719	623	508	401	317	269	501
80N	0	0	80	320	597	677	630	360	120	13	0	0	243
75N	3	20	133	340	623	693	657	410	177	57	7	0	258
70N	7	47	193	423	647	713	677	457	233	100	23	3	294
65N	27	83	253	470	670	730	700	503	297	150	50	13	329
60N	57	130	320	513	693	743	720	547	350	203	87	40	367
55N	100	187	350	553	717	757	737	590	410	257	133	77	406
50N	157	250	450	593	733	767	750	627	473	327	193	127	454
45N	220	313	513	633	753	777	763	670	533	387	257	190	501
40N	290	383	567	667	763	783	773	703	587	447	323	257	545
35N	360	453	617	700	767	783	777	727	627	503	393	320	586
30N	423	507	650	720	767	783	777	740	660	550	453	380	618
25N	477	550	677	727	763	780	770	743	683	587	500	433	641
20N	517	583	693	727	753	763	757	740	700	617	543	483	656
15N	553	610	700	720	733	740	737	727	703	640	577	523	664
10N	580	633	700	710	707	707	707	707	703	653	600	553	663
5N	600	650	693	693	680	660	670	683	693	663	620	577	657
0	617	660	680	673	640	600	623	653	680	667	633	600	644

TABLE III. Annual mean values of k' and k'' at stated latitudes

Lat.	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	Stockholm	U.S.A.
k'	0.65	0.66	0.66	0.67	0.67	0.68	0.68	0.68	0.67	0.66	0.64	0.62	0.60	0.55	0.50	0.42	0.61	0.71
k''	0.50	0.52	0.55	0.57	0.59	0.61	0.63	0.65	0.68	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.83	–
Source	Budyko (1956)																Asklöf (1920)	Kimball (1928)

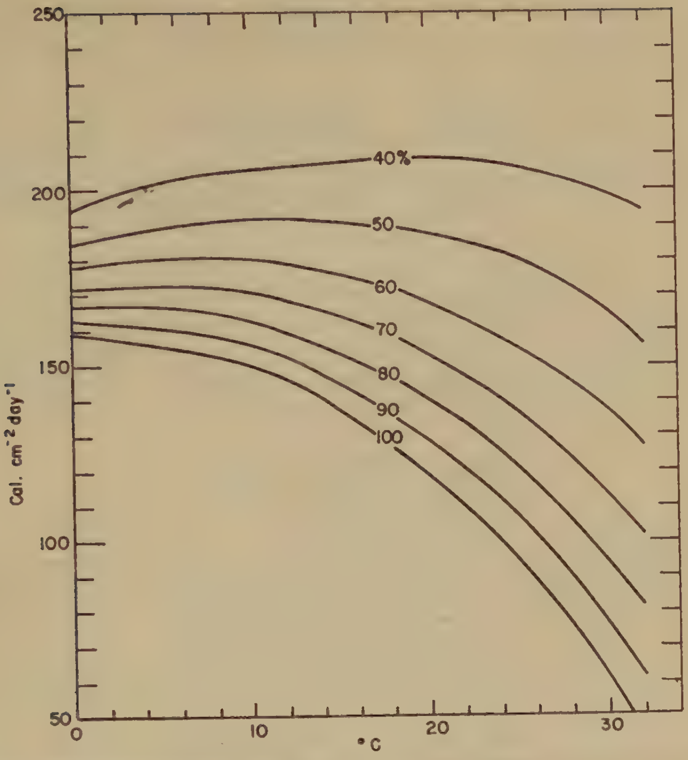

Figure 2. Effective back radiation with a clear sky and neutral stability as a function of sea surface temperature (°C) and relative humidity (%).

The amount of radiation reflected from the sea surface depends on the angle of incidence and on the roughness of the surface. Compared to a calm surface, the presence of waves reduces the amount of incoming radiation with high solar altitudes and increases it with low solar altitudes. The albedo of the sea surface for total (direct and diffuse) incoming radiation varies between 0.06 and 0.23 (Table IV), according to Budyko (1956) and Zubov (1957). Cox and Munk (1955) found that the albedo for a roughened sea surface varied between 0.02 and 0.15 for direct radiation and between 0.04 and 0.10 for diffuse radiation. For the present investigation, a value of 0.06 has been adopted.

The relation between cloud type and incident radiation has been studied by Haurwitz (1948), who found that a fully overcast day with cirrus lets 83% of a clear sky radiation through. With fog the ratio is only 18% (Table V).

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TABLE IV. ALBEDO OF THE SEA SURFACE FOR TOTAL (DIRECT + DIFFUSE) RADIATION (AFTER BUDYKO, 1956)

Lat \ *Month*	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Year*
70	—	0.23	0.16	0.11	0.09	0.09	0.09	0.10	0.13	0.15	—	—	(0.13)
60	0.20	0.16	0.11	0.08	0.08	0.07	0.08	0.09	0.10	0.14	0.19	0.21	0.13
50	0.16	0.12	0.09	0.07	0.07	0.06	0.07	0.07	0.08	0.11	0.14	0.16	0.10
40	0.11	0.09	0.08	0.06	0.06	0.06	0.06	0.06	0.07	0.08	0.11	0.12	0.08
30	0.09	0.08	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.08	0.09	0.07
20	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.07	0.06
10	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06
0	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06

TABLE V. Ratio of insolation with overcast sky to insolation with cloudless sky for an optical air mass $m = 2.5$ (after Haurwitz, 1948)

Cloud type	*Ci*	*Cs*	*Ac*	*As*	*Sc*	*St*	*Ns*	*Fog*
Ratio	0.83	0.74	0.49	0.41	0.33	0.25	0.21	0.18

The rate of heat exchange with the atmosphere through the process of evaporation can be expressed by

$$Q_e = L\rho E, \tag{5}$$

where L is the latent heat of evaporation (cal/gm), ρ the density of water (g/cm³), and E evaporation (cm/day). L decreases somewhat with temperature, but not much error is introduced in assuming it constant (585 cal/gm). As a first approximation, E can be expressed as a vertical flux of water vapor, viz:

$$E = -\frac{A}{\rho}\frac{d(\rho q)}{dz}, \tag{6}$$

where ρ is the density of air, q the specific humidity, z the height, and A the coefficient of turbulent heat exchange. A depends on wind velocity, height, and stability of the air; with neutral stability, A increases approximately linearly with height; with unstable stratification the increase is faster, with stable stratification slower.

The equation cannot be evaluated in the above form because of the difficulty in measuring humidity gradients at sea and because of uncertainties as to the coefficient of turbulent heat exchange. Instead, a semiempirical equation of the type

$$E = -K\cdot W\Delta e \tag{7}$$

is commonly used in climatological research (Jacobs, 1951; Sverdrup, 1951). Here Δe is the vapor pressure difference (mb) between the sea surface and the air above it, W the wind velocity (m/sec), and K a coefficient of proportionality which can be obtained from the boundary layer theory (Sverdrup, 1951). This coefficient decreases slightly with increasing wind velocity and altitude, as shown in Fig. 3.

The rate of heat exchange through conduction can be computed from the rate of evaporation (Q_e) and the "Bowen Ratio" (R) in accordance with equation

$$Q_c = R\cdot Q_e = 0.66 \times 10^{-3}p \times \frac{\Delta\theta}{\Delta e}\,Q_e \quad \text{(Bowen, 1926)}, \tag{8}$$

where p is the sea level atmospheric pressure and (mb) $\Delta\theta$ the sea-air temperature difference (°C); the other symbols have their previous meaning.

The heat exchange through condensation can be written formally as

$$Q_p = L \cdot \rho \cdot H, \tag{9}$$

where L is the latent heat of condensation, ρ the density of the condensed water (g/cm^3), and H the height (cm) of the water layer resulting from condensation. No direct measurements of H are available from the oceans. A rough estimate of the magnitude of heat gained by this process may be obtained by considering a dense fog (liquid water content 10^{-5}g/cm^3) of 100 m thickness laying above the sea surface. Even if all the water of the fog were available for condensation (which certainly is not the case), the amount of heat gained would be only 60 cal/cm^2. It is therefore unlikely that the condensation of water vapor affects the heat balance of the sea to any extent.

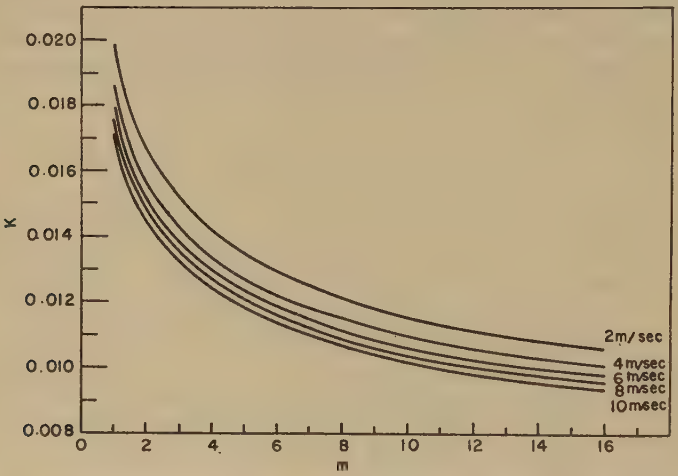

Figure 3. Evaporation coefficient K as a function of wind velocity (m/sec) and height above the sea surface (m).

The total amount of sensible heat exchange is the sum of these processes, viz.

$$Q_a = Q_e + Q_c + Q_p. \tag{10}$$

The evaporation term usually outweighs the other terms by an order of magnitude.

The rate of heat brought into the region through the process of advection can be calculated either by taking the difference from the other terms of the heat balance, viz.

$$Q_v = Q_L - Q_r - Q_a \tag{11}$$

or by using an independent expression

$$Q_v = C_p \cdot \rho \left[\int_0^z u \frac{\partial \theta}{\partial x}\, dz + \int_0^z v \frac{\partial \theta}{\partial y}\, dz + \int_0^z w \frac{\partial \theta}{\partial z}\, dz \right], \tag{12}$$

where u, v, and w are the velocity components and the other terms are as stated before. By using both equations to compute Q_v and by comparing the results, a check could be made of the accuracy of the heat balance method. As a first approximation, the horizontal velocity components can be obtained from the geostrophic method, the temperature gradients from actual measurements made at sea. The vertical velocity component can be avoided by selecting ocean areas where there is reason to assume that vertical motion is unimportant. Unfortunately several attempts to compare the advection terms obtained from the difference method and from the independent method have yielded disappointing results. At the present time it is not possible to say whether the discrepancy is due to inadequacy of the difference method or to evaluation of Q_v from eq. (12), or both.

B) SALT BALANCE. The local change of salt in a given time interval can be written as

$$S_L = S_{e-p} + S_r + S_v, \tag{13}$$

where S_L denotes the local rate of salt change, S_{e-p} the rate due to the excess of evaporation over precipitation, S_r the rate due to runoff, and S_v the rate due to advection. The units used are g cm^{-2} day^{-1}.

The local rate of change can be expressed for a water column of depth Z:

$$S_L = 10^{-3} \rho \int_0^z \frac{\partial S^*}{\partial t}\, dz, \tag{14}$$

where ρ is the density of the water column (g cm^{-3}) and S^* its salinity (‰). The integration should be carried out to a depth where the seasonal variation of salinity becomes negligible; this depth, in the region concerned, lies at 200 m. In order to evaluate eq. (14), the salinity must be known accurately to ±0.01‰.

The rate of change due to excess evaporation over precipitation is

$$S_{e-p} = (e - p)\, 10^{-3} \rho S^*, \tag{15}$$

where e is evaporation (cm/day), p precipitation (cm/day); the other quantities are as before.

The rate of change due to runoff is

$$S_r = -\frac{D}{A}\, 10^{-3} \rho S^*, \tag{16}$$

where D is the discharge (cm^3 day^{-1}), and A the area (cm^2) affected by the discharge.

The advection term is generally computed as the difference from the other terms of the salt balance, since it is difficult to evaluate it independently.

The Region off California and Baja California

A) Radiation (Tables VI, VII). The rate of total (direct + diffuse) short wave radiation received at the sea surface varies with latitude and time, with annual mean values ranging from about 300 cal cm^{-2} day^{-1} off northern California to about 450 cal cm^{-2} day^{-1} off southern Baja California. Seasonal differences between the northern and southern part of the region are greatest in winter and smallest in summer. The minimum rate of radiation is always found in December, but the maximum rate may occur in spring (Central Baja California), summer (California), or fall (southern Baja California), depending on regional differences in the seasonal variation of cloudiness. The oceanic areas receive, on the whole, considerably less radiation than comparable coastal stations, as can be seen by comparing values in Tables VI and VII. The largest differences are found during the warmer part of the year when there is a sharp increase in cloudiness from the coast toward the ocean.

Back radiation shows little seasonal or latitudinal variation. About 120 cal cm^{-2} day $^{-1}$ are lost to the atmosphere on an annual average, but there is an indication that values are somewhat lower in summer than in winter.

The difference between incoming short wave and outgoing long wave radiation is the effective radiation, which shows a seasonal and latitudinal variation similar to the incoming radiation. Annual mean values range from about 200 cal cm^{-2} day^{-1} off northern California to about 350 cal cm^{-2} day^{-1} off southern Baja California. They are in good agreement with Budyko's charts (1955, 1956).

B) Sensible Heat Exchange with the Atmosphere (Table VIII). In the California Current region this is due almost entirely to evaporation, the rates due to condensation and convection being very small.

The rate of evaporation is comparatively low and does not show appreciable seasonal or latitudinal variation. This can be explained partly by the rather low and constant wind velocities. On an annual average, between 70 and 130 cal cm^{-2} day^{-1} are lost to the atmosphere; these values agree favorably with the findings of Jacobs (1951) and

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TABLE VI. AVERAGE MONTHLY VARIATION OF TOTAL INCOMING RADIATION (Q_s), BACK RADIATION (Q_b) AND EFFECTIVE RADIATION (Q_r) IN CAL CM^{-2} DAY^{-1}

Month / Area	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
						Q_s							
A	189	226	314	363	428	438	388	379	345	266	204	156	308
B	205	242	361	410	451	462	427	379	339	285	215	181	330
C	251	288	386	433	460	470	412	367	347	316	283	243	355
D	267	307	392	426	430	438	412	388	379	326	296	250	359
E	306	328	412	427	390	367	387	378	389	369	334	286	364
F	306	344	452	492	520	515	518	519	483	403	343	290	432
G	343	391	480	516	508	501	534	534	511	452	370	322	455
H	333	403	507	538	553	547	504	504	456	452	380	322	458
						Q_b							
A	−110	−106	−109	−111	−108	−114	−94	−127	−106	−113	−112	−107	−110
B	−133	−123	−128	−129	−130	−126	−112	−101	−118	−120	−124	−131	−123
C	−136	−136	−134	−120	−128	−114	−98	−104	−127	−124	−132	−137	−124
D	−129	−138	−134	−119	−112	−112	−98	−97	−109	−121	−136	−137	−120
E	−134	−133	−131	−129	−109	−96	−100	−90	−102	−120	−137	−138	−118
F	−130	−136	−135	−136	−132	−126	−123	−111	−113	−115	−130	−136	−127
G	−126	−133	−137	−133	−138	−130	−114	−103	−100	−105	−107	−121	−121
H	−116	−132	−132	−130	−126	−115	−91	−84	−84	−93	−95	−107	−109
						Q_r							
A	79	120	205	252	320	324	294	252	239	153	92	49	198
B	72	119	233	281	321	336	315	278	221	165	91	50	207
C	115	152	252	313	332	356	314	263	220	192	151	106	231
D	138	169	258	307	318	326	314	291	270	205	160	113	239
E	172	195	281	298	281	271	287	288	287	249	197	150	246
F	176	208	317	356	388	389	395	408	370	288	213	154	305
G	217	258	343	383	370	371	420	431	411	347	263	201	334
H	217	271	375	408	427	432	413	420	372	359	285	215	349

TABLE VII. Total incoming radiation in cal cm^{-2} day^{-1} at certain shore stations in California

Month / Place	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Year*
Eureka	148	196	312	367	420	446	441	387	346	254	171	139	302
San Francisco	198	253	391	478	536	579	543	486	437	337	243	179	388
Santa Maria	252	281	376	461	499	564	567	531	464	362	275	198	403
San Diego	259	307	412	462	491	525	559	543	477	379	313	235	414

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TABLE VIII. AVERAGE MONTHLY VARIATION OF THE SENSIBLE HEAT EXCHANGE WITH THE ATMOSPHERE THROUGH EVAPORATION (Q_e) CONVECTION (Q_c) AND TOTAL HEAT EXCHANGE (Q_s) IN CAL CM^{-2} DAY^{-1}

Month / Area	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
						Q_e							
A	−88	−59	−64	−76	−88	−94	−94	−76	−64	−70	−64	−76	−76
B	−64	−59	−53	−70	−82	−88	−76	−64	−53	−70	−64	−53	−66
C	−111	−129	−117	−99	−88	−76	−94	−94	−105	−129	−111	−99	−104
D	−64	−76	−82	−76	−70	−64	−88	−88	−82	−88	−76	−59	−76
E	−105	−105	−140	−146	−158	−99	−94	−94	−76	−105	−111	−111	−112
F	−117	−117	−146	−88	−111	−82	−70	−70	−88	−129	−117	−117	−104
G	−117	−105	−105	−117	−140	−94	−76	−94	−111	−140	−123	−140	−114
H	−146	−117	−140	−140	−152	−146	−123	−99	−94	−117	−135	−140	−129
						Q_c							
A	−15	−1	5	5	7	15	10	5	11	0	−6	−5	2
B	−4	4	12	8	16	24	17	17	11	6	4	0	10
C	−2	5	7	11	7	13	8	5	14	3	7	−5	6
D	−3	2	−2	2	−1	1	−2	−2	−2	0	−2	−3	−1
E	−7	0	0	10	5	5	2	6	−2	0	−3	−9	1
F	−11	−4	1	8	6	8	7	6	3	−10	−4	−7	0
G	−11	−5	−3	7	1	10	2	−1	−3	−4	−4	−11	−1
H	−10	−6	−4	1	2	−1	−4	−5	−5	−1	−4	−10	−4
						Q_s							
A	−103	−60	−59	−71	−81	−79	−84	−71	−53	−70	−70	−81	−74
B	−68	−55	−41	−62	−66	−64	−59	−47	−42	−64	−60	−53	−56
C	−113	−124	−110	−88	−81	−63	−86	−89	−91	−126	−104	−104	−98
D	−67	−74	−84	−74	−71	−63	−90	−90	−84	−88	−78	−62	−77
E	−112	−105	−140	−136	−153	−94	−92	−88	−78	−105	−114	−120	−111
F	−128	−121	−145	−80	−105	−74	−63	−64	−85	−139	−123	−124	−104
G	−128	−110	−108	−110	−139	−84	−74	−95	−114	−144	−127	−151	−115
H	−156	−123	−144	−139	−150	−149	−127	−104	−99	−118	−139	−150	−133

Budyko (1955, 1956). The rate of evaporation is somewhat larger in the southern than in the northern part of the region.

The rate of heat exchange through convection is generally less than 10% of that through evaporation. During spring and summer months the sea gains small amounts of heat from the atmosphere whereas during fall and winter months it loses a small amount. The amounts exchanged are so small in comparison with evaporation that they can be neglected.

The rate of heat change through condensation can be completely neglected.

The rate of total exchange of sensible heat with the atmosphere is therefore approximately equal to the rate of evaporation.

C) Local Heating and Advection (Table IX). The average monthly variation of the rate of local heat change shows that heat is gained principally between July and September and lost mainly between November and January. These gains and losses are somewhat more pronounced in the southern than in the northern part of the region. The time lag in the occurrence of the maximum rate of heat gain and the maximum rate of radiation strongly suggest that advection may be an important process in the California Current region.

The rate of advection, when computed from the other terms of the heat balance, varies between about 130 and 230 cal cm^{-2} day^{-1} on a yearly average; this value is in good agreement with figures obtained by Budyko (1955, 1956), who gives 200 cal cm^{-2} day^{-1} for the southern part of the California Current region. The loss of heat through advection of cold water appears to be largest during winter and spring and smallest in fall. Only in isolated places, such as that off southern Baja California in fall, is there some gain of heat through advection of warm water.

From the other terms of the heat balance, an attempt was made to evaluate the rate of advection independently. Area E off central Baja California was chosen for this purpose because it is sufficiently far away from the coast to be markedly influenced by upwelling. It was found that on an annual average the rate of advection amounted to 203 cal cm^{-2} day^{-1} as compared to 135 cal cm^{-2} day^{-1} obtained by the difference method. However, comparison of the average monthly variation of the rate of advection (Fig. 4) shows that there is little similarity between both curves.

D) Salt Balance (Table X). The observed rate of local salt change does not show a simple seasonal variation. Off central California there is a salt gain in summer by upwelling and a gain in winter

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TABLE IX. AVERAGE MONTHLY VARIATION OF LOCAL HEAT CHANGE (Q_L) AND ADVECTION (Q_v) IN CAL CM^{-2} DAY^{-1}

Month / Area	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
						Q_L							
B	−147	−83	−32	−32	6	90	102	70	52	90	12	−128	0
C	−83	−51	−46	26	77	83	102	186	198	−121	−256	−115	0
D	−141	−83	−32	−70	−26	173	237	166	128	51	−166	−237	0
E	−109	−115	−64	−20	58	128	134	90	179	83	−198	−166	0
F	−307	−205	−166	−204	−26	205	256	307	542	173	−294	−281	0
G	−154	−237	−83	51	90	90	96	230	525	−58	−467	−83	0
						Q_v (by difference)							
B	−151	−147	−224	−251	−249	−182	−154	−161	−127	−11	−19	−131	−151
C	−85	−78	−188	−199	−174	−210	−126	12	69	−187	−303	−117	−133
D	−212	−178	−206	−303	−273	−90	13	−35	−58	−66	−248	−288	−162
E	−169	−205	−205	−182	−70	−49	−61	−110	−30	−61	−281	−196	−135
F	−355	−292	−338	−480	−309	−110	−76	−37	257	24	−384	−311	−201
G	−243	−385	−318	−222	−141	−197	−250	−86	228	−261	−613	−133	−219

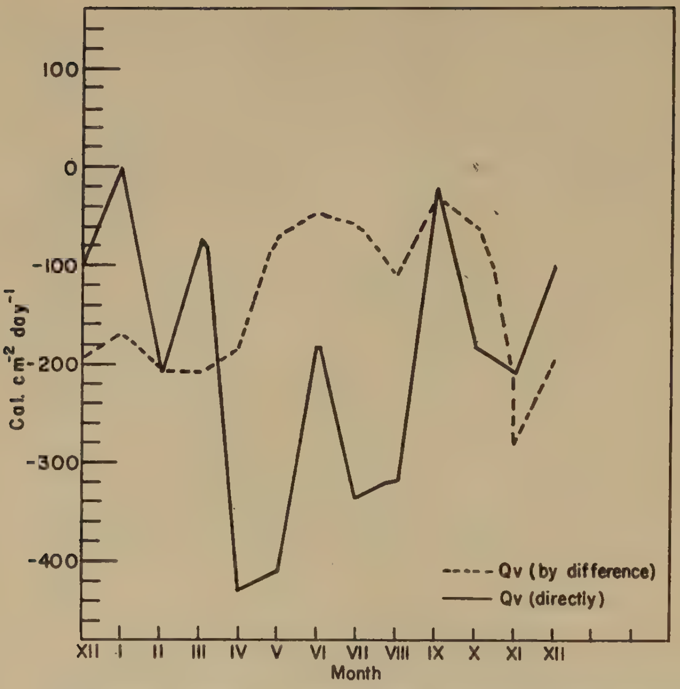

Figure 4. Average monthly variation of advection of heat (Q_v) in area *E* off central Baja California. Dotted curve represents Q_v found by difference from the other terms of the heat balance; solid line shows Q_v determined independently.

through advection from the west. Off southern California the gain occurs in spring and is probably related to upwelling. Off Baja California there is a gain from about May to September and again in December.

The rate of salt change due to excess evaporation over precipitation shows a summer maximum off California and a spring maximum off Baja California. Generally this represents a gain of salt, except in the northern part of the region, during winter. Annual mean values range from about 50 g cm^{-2} day^{-1} off Baja California to about -10 g cm^{-2} day^{-1} off central California.

The rate of change due to advection shows features similar to the local salt change. There is a loss of salt through advection on an annual average in all of the areas except in that off central California.

E) Errors of the Heat and Salt Balance Method. The accuracy of the heat and salt balance method depends on the soundness of

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TABLE X. AVERAGE MONTHLY VARIATION OF LOCAL SALT CHANGE (S_L), SALT CHANGE DUE TO EXCESS EVAPORATION OVER PRECIPITATION (S_{e-p}) AND SALT CHANGE DUE TO ADVECTION (S_v) IN G CM^{-2} DAY^{-1}

Month / Area	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
						$10^4 \times S_L$							
B	67	0	−134	−201	134	201	134	134	67	−201	−268	67	0
C	−335	−67	−67	134	268	268	134	−268	−67	201	67	−268	0
D	−201	0	268	268	134	−67	−201	−67	201	0	−134	−201	0
E	0	−134	−67	−134	−134	268	335	201	134	−268	−268	67	0
F	0	−201	−268	−201	67	201	67	67	335	67	−268	134	0
G	67	−201	−67	0	201	134	0	0	67	−335	−201	335	0
						$10^4 \times S_{e-p}$							
B	−95	−75	−58	−3	27	48	44	37	24	14	−31	−88	−13
C	14	17	24	43	41	43	55	51	58	61	41	0	37
D	−14	−14	3	24	31	37	51	48	44	37	20	−24	20
E	34	31	58	75	88	58	51	44	20	51	51	27	49
F	65	65	85	51	65	48	34	20	7	68	61	48	51
G	65	48	61	68	82	54	37	7	7	71	58	44	50
						$10^4 \times S_v$							
B	162	75	−76	−198	−107	153	90	97	43	−215	−237	155	13
C	−349	−84	−91	91	227	225	79	−319	−125	140	26	−268	−37
D	−187	14	265	244	103	−104	−252	−115	157	−37	−154	−177	−20
E	−34	−165	−125	−209	−222	210	284	157	114	−319	−319	40	−49
F	−65	−266	−343	−252	2	153	33	47	328	−1	−329	86	−51
G	2	−249	−128	−68	119	80	−37	−7	60	−406	−259	291	−50

the assumptions underlying the theory, on the reliability of the data, and on the magnitude of random and systematic errors.

Accepting the theory as correct, the effect of observational errors upon the different terms is shown in Table XI. An error in estimating cloudiness by one tenth changes the rate of incoming radiation by 10% and of back radiation by 4%, on an average. The effect of an error of 0.1°C in determining the sea-air temperature difference alters the rate of back radiation by 1% and of sensible heat exchange through convection by about 3%. An error of 1 m/sec in estimating wind velocity changes the rate of evaporation between 10 and 20% for wind velocities most commonly observed in the California Current region. An error of 1% in determining humidity changes the rate of evaporation by 5% and the rate of back radiation by 1%. Small errors in determining temperature and salinity changes from one month to the next lead to appreciable errors in the rates of local heat and salt change.

Summarizing, it may be said that the rate of effective radiation calculated from the theory is accurate within 20%, the rate of exchange of sensible heat by the atmosphere within 40%, and the rate of local heat and salt change within about 20%. The advection term calculated by difference from the other terms of the balance is therefore accurate only within 80%. The error in calculating the advection term directly from the horizontal (geostrophic) velocity components and temperature gradients is estimated to be roughly 50%.

F) NONSEASONAL VARIATIONS. The nonseasonal variation of heat balance terms may be estimated by taking the difference between the monthly mean and the long term mean of the same month for various contributing factors and plotting these anomalies against time.

The monthly cloudiness anomalies (tenths) for the period 1921–1938, shown in Fig. 5, vary mostly between ±0.2 and none are greater than ±0.4. These anomalies produce a change in the rate of incoming radiation on the order of ±20% and of back radiation on the order of ±10%.

Anomalies in the northerly wind component at Lat. 30N between Long. 110W–130W and at Lat. 40N between Long. 120W–130W for the period 1920–1958 are shown in Fig. 6. The velocities, obtained from pressure differences, must be multiplied by a factor of 0.6 in order to make them applicable near the sea surface. It is seen that, near sea level, the wind anomalies are on the order of ±2 m/sec at Lat. 30N and ±3 m/sec at Lat. 40N. The change in the rate of

TABLE XI. PERCENTAGE ERROR OF HEAT BALANCE AND SALT BALANCE TERMS

	Error in		
Cloudiness C *tenths*	*cloudiness* ΔC *tenths*	*incoming radiation* $\frac{\Delta Q_s}{Q_s}$ %	*back radiation* $\frac{\Delta Q_b}{Q_b}$ %
0.0	±0.1	∓ 7	∓ 0
0.2	±0.1	∓ 8	∓ 1
0.4	±0.1	∓ 9	∓ 3
0.6	±0.1	∓12	∓ 5
0.8	±0.1	∓15	∓ 8
1.0	±0.1	∓21	∓17

	Error in		
Sea-air temp. diff. $\theta_s - \theta_a$ °C	*sea-air temp. diff.* $\Delta(\theta_s - \theta_a)$ °C	*back radiation* $\frac{\Delta Q_b}{Q_b}$ %	*convection* $\frac{\Delta Q_c}{Q_c}$ %
1.0	±0.1	±1	±10
2.0	±0.1	±1	± 5
3.0	±0.1	±1	± 3
4.0	±0.1	±1	± 3
5.0	±0.1	±1	± 2
6.0	±0.1	±1	± 2

	Error in	
Wind velocity W *m/sec*	*wind vel.* ΔW *m/sec*	*evaporation* $\frac{\Delta Q_e}{Q_e}$ %
2	±1	±50
4	±1	±25
6	±1	±17
8	±1	±13
10	±1	±10
12	±1	± 8
14	±1	± 7
16	±1	± 6

	Error in		
Humidity %	*humidity* Δ %	*evaporation* $\frac{\Delta Q_e}{Q_e}$ %	*back radiation* $\frac{\Delta Q_b}{Q_b}$ %
60	±1	∓ 2	∓1
65	±1	∓ 3	∓1
70	±1	∓ 3	∓1
75	±1	∓ 4	∓1
80	±1	∓ 5	∓1
85	±1	∓ 7	∓1
90	±1	∓10	∓1
95	±1	∓20	∓1

	Error in	
Temp. diff. per mo. θ °C	*temp. diff. per mo.* $\Delta\theta$ °C	*local heat change* $\frac{\Delta Q_L}{Q_L}$ %
0.2	±0.1	±50
0.4	±0.1	±25
0.6	±0.1	±17
0.8	±0.1	±13
1.0	±0.1	±10
1.2	±0.1	± 8
1.4	±0.1	± 7
1.6	±0.1	± 6

	Error in	
Salinity diff. per mo. S ‰	*sal. diff. per mo.* ΔS ‰	*local salt change* $\frac{\Delta S_L}{S_L}$ %
0.02	±0.01	±50
0.04	±0.01	±25
0.06	±0.01	±17
0.08	±0.01	±13
0.10	±0.01	±10
0.15	±0.01	± 7
0.20	±0.01	± 5
0.25	±0.01	± 4

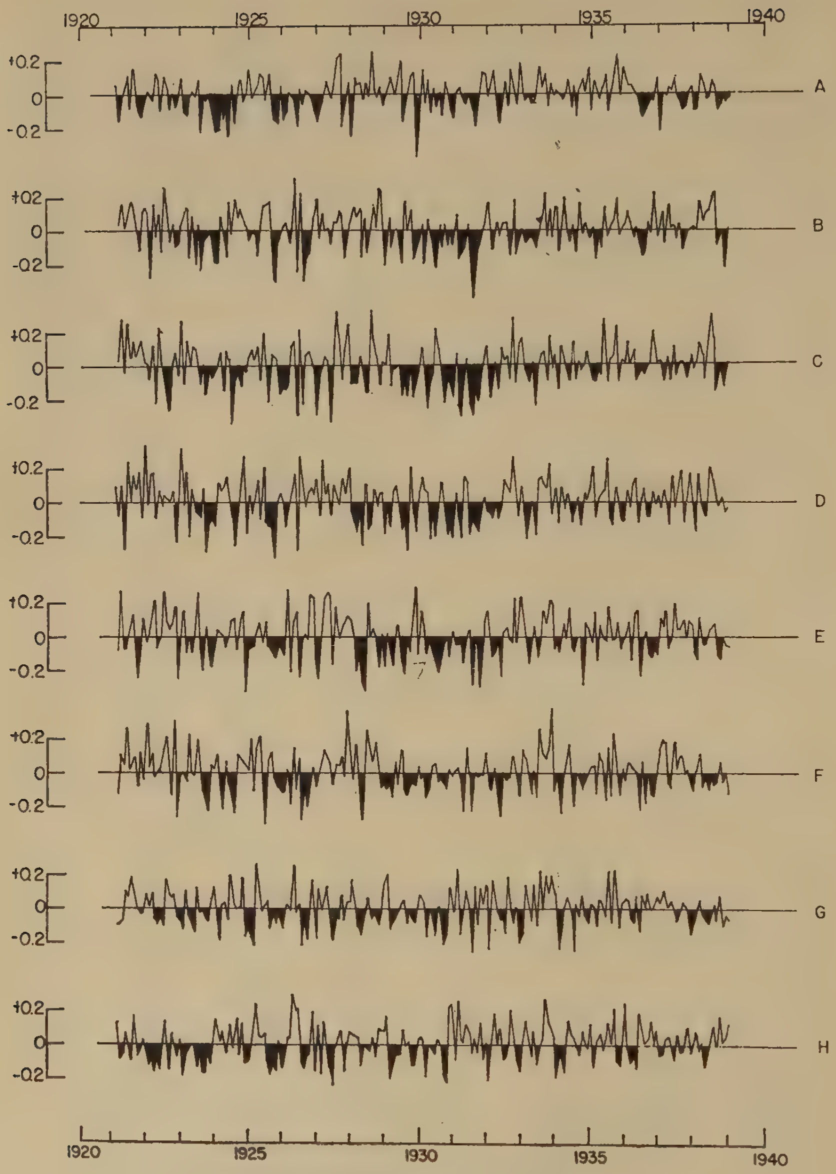

Figure 5. Monthly cloudiness anomaly in tenths.

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evaporation and convection produced by these anomalies is on the order of ±50% at Lat. 30N and ±75% at Lat. 40N.

Nonseasonal variations in temperature change from one month to the next are generally within ±0.3°C/mo. The change in the rate of local heating produced by these anomalies is within ±60%.

Anomalies in salinity change per month fall mostly within ±0.02‰/mo and produce changes in the local salt content by about ±50%.

It might seem that changes produced by nonseasonal variations are not much larger than changes that could be produced by errors in observation; however, the errors discussed in the previous section apply to individual observations; by taking monthly averages of many stations, we may expect that random errors will be reduced to a minimum and that nonseasonal changes are therefore larger than errors due to observation.

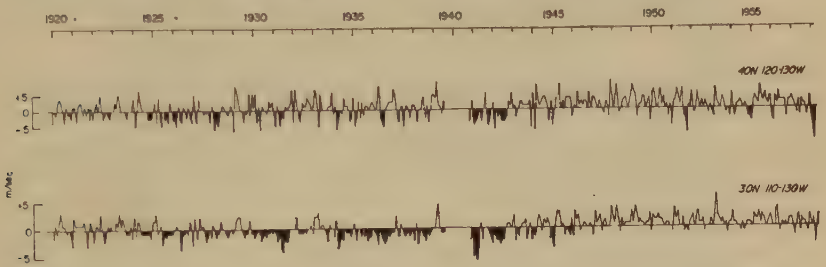

Figure 6. Monthly anomaly of northerly (geostrophic) wind component, expressed in millibars of pressure difference.

Conclusions. Investigations of the heat and salt balance in the California Current region show that the rate of local heat change is primarily related to the rate of effective radiation and the rate of advection. The rate of turbulent heat exchange with the atmosphere is rather small and constant. The rate of local salt change is influenced principally by the rate of advection and less so by the rate of excess evaporation over precipitation. The rates of radiation and local heating are accurate within 20%, and the rate of turbulent heat exchange is accurate within 40%. An attempt to evaluate the advection term independently and to compare it to the advection term obtained by difference showed disappointing results.

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REFERENCES

Anderson, E. R.
1952. The exchange of energy between a body of water and the atmosphere with application to evaporation. Doctoral dissertation, University of California, Los Angeles. 121 pp.

Asklöf, Sven
1920. Über den Zusammenhang zwischen der nächtlichen Wärmeausstrahlung, der Bewölkung und der Wolkenart. Geogr. Ann., Stockh., *3:* 1–7.

Berliand, M. E. and T. G. Berliand
1952. Opredelenie effektivnovo izluchenia zemli s uchetom vlijania oblachnosti. Izv. ANSSSR, geophys. ser. *1.*

Black, J. N.
1956. The distribution of solar radiation over the earth's surface. Arch. Met. Geophys. (B) *7:* 166–189.

Bowen, I. S.
1926. The ratio of heat losses by conduction and by evaporation from any water surface. Phys. Rev., *27:* 779–787.

Budyko, M. I. (editor)
1955. Atlas teplovo balansa. GIMIZ, Leningrad.
1956. Teplovoi balans zemnoi poverkhnosti. GIMIZ, Leningrad. 256 pp.

Burdecki, Feliks
1958. Remarks on the distribution of solar radiation on the surface of the earth. Arch. Met. Geophys. (B) *8:* 326–335.

Cox, Charles and W. H. Munk
1955. Some problems in optical oceanography. J. mar. Res., *14*(1): 63–78.

Haurwitz, Bernhard
1948. Isolation in relation to cloud type. J. Met., *5:* 110–113.

Imperial Marine Observatory, Kobe, Japan
1911–1938. The mean atmospheric pressure, cloudiness, air and sea surface temperature in the North Pacific Ocean and the neighbouring seas.

Jacobs, W. C.
1951. The energy exchange between the sea and the atmosphere and some of its consequences. Univ. Calif. Press, Berkeley and Los Angeles. 122 pp.

Kimball, H. H.
1928. Amount of solar radiation that reaches the surface of the earth on the land and the sea. Mon. Weath. Rev., Wash., *56:* 383–389.

KOIZUMI, M.
1956. Researches on the variation of oceanographic conditions in the region of the ocean weather station "EXTRA" in the North Pacific Ocean (III). Pap. Met. Geophys., *6:* 273–284.

OCEANIC OBSERVATIONS OF THE PACIFIC
(in press) Data report for 1956 and 1957. Univ. Calif. Press, Berkeley and Los Angeles.

PATULLO, JUNE G.
1957. The seasonal heat budget of the oceans. University of California, Los Angeles. Doctoral Dissertation, 104 pp.

SVERDRUP, H. U.
1951. Evaporation from the oceans, in Compendium of Meteorology; Amer. met. Soc.; 1071–1081.

TABATA, SUSUMU
1958. Heat budget of the water in the vicinity of Triple Island, British Columbia. J. Fish. Res. Board Canada, *15*(3): 429–451.

U. S. HYDROGRAPHIC OFFICE
1956. Pilot charts for the North Pacific Ocean. Washington D. C.

U. S. WEATHER BUREAU
(unpublished) Mean monthly sea level atmospheric pressure charts for the northern hemisphere, 1899–1958. Washington, D. C.

ZUBOV, N. N.
1957. Okeanologicheskie tablitsy. GIMIZ Leningrad. 408 pp.

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THEORETICAL PROOF OF THE EXISTENCE OF CHARACTERISTIC DIFFUSE LIGHT IN NATURAL WATERS[1]

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ABSTRACT

This paper develops a mathematical model for the radiance distribution of light penetrating a homogeneous hydrosol on the basis of the general theory of radiative transfer. It is proved that the radiance distribution approaches an asymptotic pattern at great depths. This is in accord with previous field measurements of the directional patterns in underwater light and with L. V. Whitney's conjecture that there is at some depth in natural waters a characteristic diffuse light symmetrically distributed around the vertical. The angular form of this equilibrium light pattern is derived in terms of the mathematical model presented.

INTRODUCTION

Recent experimental evidence (Tyler, 1958) forms the basis for fresh support of the long-standing conjecture that the radiance distribution about a point in an optically deep natural hydrosol approaches, with increasing depth, a characteristic form which is independent of the external lighting conditions and of the optical state of the medium's surface and which depends only on the inherent optical

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properties of the medium. This conjecture was apparently given its first definitive formulation by Whitney (1941a, 1941b), who referred to the asymptotic radiance distribution as *characteristic diffuse light.* (Some early experimental evidence for this conjecture is cited in Whitney's papers.) In this note we complement experimental evidence in favor of this conjecture by supplying a simple mathematical proof of the existence of characteristic diffuse light in all homogeneous optically deep natural waters. The paper concludes with a derivation of the integral equation governing the angular structure of characteristic diffuse light as well as a brief discussion of an interesting and tractable example for the case of isotropic scattering.

We note in passing that the applicability of Whitney's hypothesis has been widened considerably since its formulation. The problem of a limiting angular distribution has since been encountered in modern neutron transport theory, basically as an abstract mathematical problem rather than as an experimental phenomenon. A similar type of problem has long been extant in astrophysical radiative transfer. A general proof of the existence of an asymptotic radiance distribution which covers all of these contexts recently has been devised (Preisendorfer, 1958a).

However, the hypothesis still retains its greatest usefulness in the context of geophysical optics. For in this field, unlike the others mentioned above, the trend to a characteristic limiting form is a directly observable phenomenon. Furthermore, the existence of such a form is of inestimable importance to all experimental research work dealing with the determination of optical properties of natural waters. In many important instances, knowledge that an asymptotic radiance distribution exists will obviate the necessity of experimental probings to extremely large depths; for such knowledge will allow, by means of relatively simple formulae, accurate prediction of the geometrical structure of the light field in great-depth ranges. Some of these practical consequences of the asymptotic radiance hypothesis have been formulated recently (Preisendorfer 1958b).

PHYSICAL BACKGROUND OF THE METHOD OF PROOF

The argument used by Whitney in establishing experimental evidence for the asymptotic radiance hypothesis went basically as follows: he showed that when experimentally obtained plots of radiance distributions at various large depths were blown up to the same size (more precisely, the zenith readings were normalized to a common value), they formed a set of nearly congruent figures. Now, an interesting feature of such distributions is that they assume the same

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shape and decrease in size with increasing depth at nearly the same exponential rate. This fact can be stated precisely as follows:[2]

$$N(z, \theta, \phi) = g(\theta, \phi)e^{-kz}. \tag{1}$$

From this we see that the asymptotic radiance hypothesis is equivalent to the statement that *the directional and depth dependence of radiance distributions multiplicatively uncouple at great depths.* That is, the radiance function N may be represented as the product of two functions: g which gives the shape or directional structure common to all distributions and an exponential function which gives the depth dependence of the distributions.

Each factor on the right-hand side of (1) has special physical significance. The function g evidentally defines the angular form of characteristic diffuse light. The exponent k of the exponential function has the following interesting interpretation.

Define *scalar irradiance* $h(z)$ at depth z as follows:

$$h(z) = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} N(z, \theta, \phi) \sin \theta \, d\theta \, d\phi. \tag{2}$$

The quantity $h(z)$ is then a measure of the volume density of radiant energy at depth z. Measurements of $h(z)$ over the years in many hydrosols have shown that $h(z)$ varies essentially in an exponential manner with depth. That is, semilog plots of $h(z)$ *vs* depth show an unmistakable trend toward linearity as depth increases. In any event, $h(z)$ may be accurately represented by a general formula of the type

$$h(z) = h(o) \exp\left\{-\int_0^z k(z')\, dz'\right\}, \tag{3}$$

where $k(z)$ is the negative logarithmic derivative of $h(z)$. (Here and below, a primed symbol refers to a dummy variable of integration.) As depth increases, experimental evidence gathered in the field indicates that $k(z)$ approaches a constant value. Denote this limit value by k_∞. Now, assuming that an asymptotic radiance distribution is approached by the radiance distributions in a particular body of water, we see from (1), (2) and (3) that

$$h(z) = h(z_0)e^{-k_\infty(z-z_0)} = e^{-kz} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} g(\theta, \phi) \sin \theta \, d\theta \, d\phi, \tag{4}$$

---

[2] It is implicit in the definition of radiance that it applies to an arbitrary but fixed wavelength of radiant flux. This is also true of all the other radiometric quantities used in this note.

where z_0 is the depth below which we may assume that $k(z) = k_\infty$. From this we conclude that

$$k = k_\infty. \tag{5}$$

Hence, under the above assumption (1) we see that, at great depths, the size of a radiance distribution plot decreases exponentially with increasing depth and that the rate of this decrease is precisely that of scalar irradiance (or energy density).

The close connection between the depth dependence of scalar irradiance and that of the radiance distributions, as summarized in (5), suggests the following mode of representation of the radiance distributions for any depth: Define, for each direction (θ, ϕ),

$$K(z, \theta, \phi) = \frac{-1}{N(z, \theta, \phi)} \frac{dN(z, \theta, \phi)}{dz}. \tag{6}$$

Then, in analogy to (3), $N(z, \theta, \phi)$ at any depth z may be represented exactly by

$$N(z, \theta, \phi) = N(0, \theta, \phi) \exp\left\{- \int_0^z K(z', \theta, \phi)\, dz'\right\}. \tag{7}$$

Now suppose there is some depth z_0 below which we have $K(z, \theta, \phi) = k_\infty$ for all directions (θ, ϕ). Then (7) may be written

$$\begin{aligned} N(z, \theta, \phi) &= N(0, \theta, \phi) \exp\left\{- \int_0^{z_0} K(z', \theta, \phi)\, dz' - \int_{z_0}^{z} K(z', \theta, \phi)\, dz'\right\} \\ &= N(z_0, \theta, \phi) \exp\{- k_\infty(z - z_0)\}. \end{aligned}$$

If we set

$$g(\theta, \phi) = N(z_0, \theta, \phi) \exp\{k_\infty z_0\},$$

then we may write

$$N(z, \theta, \phi) = g(\theta, \phi)\, e^{-k_\infty z}, \tag{8}$$

for all depths z below z_0.

The similarity between (1) and (8) is unmistakable and it points out a method of attack we may follow in order to prove the asymptotic radiance hypothesis: we must show that the quantities $K(z, \theta, \phi)$ approach a limit as depth is increased and that this limit is independent of the directions (θ, ϕ). Furthermore, this limit, in accordance with the preceding discussion, should be none other than the limit k_∞ of $k(z)$, as defined in (3).

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THE PROOF

We make use of the equation of transfer for radiance:

$$\frac{dN(z, \theta, \phi)}{dr} = -\alpha N(z, \theta, \phi) + N_*(z, \theta, \phi), \tag{9}$$

where

$$N_*(z, \theta, \phi) = \int_{\phi'=0}^{2\pi} \int_{\theta'=0}^{\pi} \sigma(\theta, \phi; \theta', \phi')\, N(z, \theta', \phi') \sin \theta' \, d\theta' \, d\phi' \tag{10}$$

defines the path function N_*; σ is the volume scattering function (which governs the law of scattering in the water) and α is the volume attenuation coefficient. The formal solution of (9) is readily obtained:

$$N(z, \theta, \phi) = N^0(z, \theta, \phi) + \int_0^r N_*(z', \theta, \phi)\, e^{-\alpha(r-r')}\, dr'. \tag{11}$$

The first term represents the component of N consisting of unscattered light. The second represents the space light over the path of length r (Fig. 1) which has been generated by light scattered into the path of sight all along its extent. The formal solution (11) has been written for a general downward direction of flow of light (see Fig. 1) so that $N^0(z, \theta, \phi)$ is interpreted as the directly transmitted light from the upper boundary of the medium and is of the form

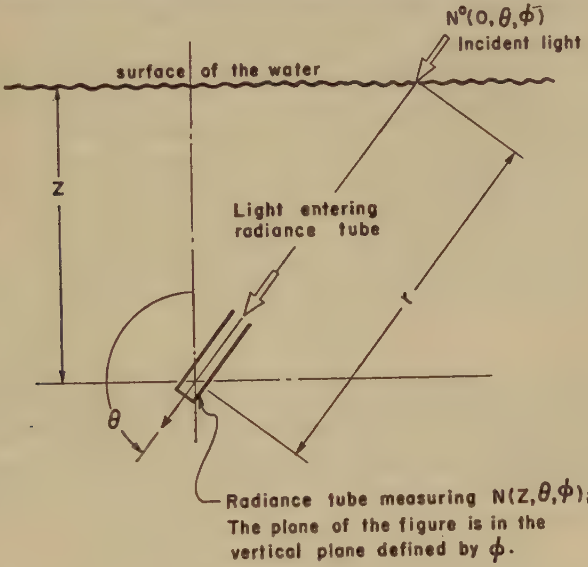
N°(0,θ,φ)
Incident light
surface of the water
z
Light entering radiance tube
r
θ
Radiance tube measuring N(Z,θ,φ); The plane of the figure is in the vertical plane defined by φ.

Figure 1

$$N^0(z, \theta, \phi) = N^0(0, \theta, \phi)\, e^{-\alpha r},$$

where

$$-r \cos \theta = z.$$

We now turn eq. (11) into a useful inequality by means of the following three steps:

First, since $N(z, \theta, \phi)$ clearly exceeds its spacelight component at all depths, we write

$$N(z, \theta, \phi) > \int_0^r N_*(z', \theta, \phi)\, e^{-\alpha(r-r')}\, dr'.$$

Second, using the definition of N_*, we strengthen the inequality when we write

$$N(z, \theta, \phi) > \sigma_{\min} \int_0^r h(z')\, e^{-\alpha(r-r')}\, dr',$$

where $\sigma_{\min}$ is the minimum value of the volume scattering function; that is, we have used (10) to deduce that

$$N_*(z, \theta, \phi) > \sigma_{\min} \int_{\phi'=0}^{2\pi} \int_{\theta'=0}^{\pi} N(z, \theta', \phi') \sin \theta'\, d\theta'\, d\phi' = \sigma_{\min} h(z).$$

Finally, since $h(z)$ decreases with increasing depth, we certainly strengthen the inequality by writing

$$N(z, \theta, \phi) > \sigma_{\min}\, h(z) \int^r e^{-\alpha(r-r')}\, dr'.$$

That is, we have

$$N(z, \theta, \phi) > \frac{\sigma_{\min}}{\alpha} h(z)(1 - e^{-\alpha r}) \tag{12}$$

for all depths z. From this we see that, as depth increases indefinitely, the exponential rate of decrease $K(z, \theta, \phi)$ of the radiance cannot eventually exceed the $k(z)$ of scalar irradiance and remain larger by any finite amount; if it did, the plot of N would eventually fall and remain below that of h. This observation is stated symbolically as follows:

$$\lim_{z \to \infty} K(z, \theta, \phi) \leqslant \lim_{z \to \infty} k(z) = k_\infty \tag{13}$$

for all downward directions (θ, ϕ). We now show that strict equality must hold in (13). We achieve this by initially assuming the contrary; that is, we assume that there is a nonzero solid angle Ω_0 of directions over which

$$\lim_{z \to \infty} K(z, \theta, \phi) \leqslant k_\infty - \epsilon,$$

where ϵ is *any* small positive number. Then it is clear that the radiances in this set of directions decrease at a definitely smaller rate than scalar irradiance; so much smaller in fact that, by our assumption, for some depth z_1 we must have

$$\int_{\Omega_0} N(z_1, \theta, \phi) \sin\theta \, d\theta \, d\phi > h(z_1).$$

However, this conclusion clearly contradicts (2) since a part cannot exceed the whole. We have reached a contradiction which leaves only one other possibility:

$$\lim_{z \to \infty} K(z, \theta, \phi) = k_\infty \tag{14}$$

for all downward directions (θ, ϕ). In the light of the preceding discussion [*cf* (8)], this means that the shape of the radiance distributions impinging on the upper boundaries of deep layers of water eventually assume a fixed form. But it is known that the shape of the *reflected* radiance distribution at the upper boundary of a scattering layer is determined by the shape of the incident radiance distribution at that boundary. Hence if the incident radiance distribution approaches a fixed shape, so does that of the reflected distribution. This completes the proof.

We observe that the present proof can also be applied in all natural waters which eventually become homogeneous. That is, the preceding arguments are basically unchanged if the medium is inhomogeneous over any initial finite depth range below the surface. Even more general media exist which give rise to asymptotic radiance distributions, namely media in which the ratio σ/α eventually becomes independent of depth (Preisendorfer, 1958a).

THE EQUATION FOR CHARACTERISTIC DIFFUSE LIGHT

Using the equation of transfer, definition (6), and the relation between z and r, we write the equation of transfer in the following general form:

$$N(z, \theta, \phi) = \frac{N_* \, (z, \phi, \theta)}{\alpha + K(z, \theta, \phi) \cos\theta}. \tag{15}$$

From (14) and (8) we see that the limiting form of (15) (as depth increases indefinitely) is

$$g(\theta, \phi) = \frac{\int_{\phi'=0}^{2\pi} \int_{\theta'=0}^{\pi} \sigma(\theta, \phi; \theta', \phi') \, g(\theta', \phi') \sin\theta' \, d\theta' \, d\phi'}{\alpha + k_\infty \cos\theta}; \tag{16}$$

this is the equation governing the angular form of characteristic diffuse light. It is a property of equations of the type shown in (16) that the function g is independent of ϕ for all real physical situations. Thus characteristic diffuse light is always represented by a surface of revolution whose axis of symmetry is vertical.

The theory of the solution of such equations as (16) is fairly well understood (*e.g.*, see Davison, 1957). The present note, therefore, will not discuss (16) in any detail. However, there is one simple special case which is immediately solved and which can shed much light on some of the salient details of the structure of the asymptotic radiance distributions. This is the case of isotropic scattering, where the volume scattering function σ is independent of direction and has the form

$$\sigma(\theta, \phi; \theta', \phi') = \frac{s}{4\pi}, \tag{17}$$

where s is the total scattering coefficient.

To observe the resulting structure of the asymptotic radiance distribution it is convenient in the present case to turn to (15). With assumption (17) and definitions (2) and (10), we have

$$N(z, \theta, \phi) = \frac{s}{4\pi} \frac{h(z)}{\alpha + K(z, \theta, \phi) \cos \theta},$$

which at great depths approaches the form

$$N(z, \theta, \phi) = \frac{1}{4\pi} \left(\frac{s}{\alpha}\right) \frac{h(z_0)\, e^{-k_\infty (z - z_0)}}{1 + \left(\frac{k_\infty}{\alpha}\right) \cos \theta}. \tag{18}$$

Here z_0 is the depth below which $h(z)$ decreases exponentially with increasing depth. Comparing (18) with (8), we see that for the present case

$$g(\theta, \phi) = \frac{1}{4\pi} \left(\frac{s}{\alpha}\right) \frac{h(z_0)\, e^{k_\infty z_0}}{1 + \left(\frac{k_\infty}{\alpha}\right) \cos \theta}. \tag{19}$$

We have written (19) in the indicated form to point up the following geometric fact: A polar plot of $g(\theta, \phi)$ is generally a prolate ellipsoid of revolution with vertical axis and of eccentricity k_∞/α. When there is no absorption in the medium, it is easy to deduce then that $k_\infty = 0$ and that characteristic diffuse light is represented by a sphere. On the other hand, if there is little scattering as compared to absorption, the figure assumes a narrow pencil-like shape. In the limit of no

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scattering, k_∞ approaches α, and the figure degenerates into a vertical line.

The structure of the expression in (18) is related to the limiting form of a simple model for the radiance distribution discussed elsewhere (Preisendorfer, 1958c) and to a formula derived by Poole (1945). We conclude with the observation that (19) predicts a different limiting ratio of horizontal to upward radiance than that derived by Whitney (1941a) under the same circumstances (*i.e.*, isotropic scattering). Instead of the ratio 2:1, as suggested by Whitney, the present formula yields

$$\frac{g(\pi/2, \phi)}{g(0, \phi)} = 1 + \left(\frac{k_\infty}{\alpha}\right) \leqslant 2. \qquad (20)$$

In other words, the ratio in (20) is not a fixed magnitude but depends on the optical properties of the medium in the manner shown.

The distribution (19) can serve as a convenient standard reference distribution against which experimentally determined radiance distributions can be compared. The amount of departure of the experimental distributions from (19) would then serve as a measure of the anisotropy of scattering in the real medium.

REFERENCES

DAVISON, B.

1957. Neutron transport theory. Clarenden Press, Oxford. 450 pp.

POOLE, H. H.

1945. The angular distribution of submarine daylight in deep water. Sci. Proc. R. Dublin Soc., *24:* 29–42.

PREISENDORFER, R. W.

1958a. A proof of the asymptotic radiance hypothesis. Visibility Laboratory Report, Scripps Institution of Oceanography, University of California. SIO Ref. 58–57.

1958b. Some practical consequences of the asymptotic radiance hypothesis. Visibility Laboratory Report, Scripps Institution of Oceanography, University of California. SIO Ref. 58–60.

1958c. Model for radiance distributions in natural hydrosols. Visibility Laboratory Report, Scripps Institution of Oceanography, University of California. SIO Ref. 58–42.

TYLER, J. E.

1958. Radiance distribution as a function of depth in the submarine environment. Visibility Laboratory Report, Scripps Institution of Oceanography, University of California. SIO Ref. 58–25.

WHITNEY, L. V.

1941a. The angular distribution of characteristic diffuse light in natural waters. J. Mar. Res., *4:* 122–131.

1941b. A general law of diminuation of light intensity in natural waters and the percent of diffuse light at different depths. J. opt. Soc. Amer., *31:* 714–722.

(Reprinted from Nature, Vol. 183, *pp.* 1820–1821, *June* 27, 1959)

Electrical Response to Illumination of the Euphausiid Crustacean Eye

WE have obtained reliably reproducible measurements of the electric potentials developed in the eyes of euphausiid crustaceans during stimulation by light. Such measurements may provide an objective method for the laboratory study of vision and photoregulated behaviour in planktonic forms which undergo vertical migrations too extensive to be duplicated experimentally with any available equipment. Preliminary observations of two species from the San Diego Trough off California, and one from Loch Fyne in Scotland, are presented here.

The specimens were collected with standard plankton nets and carried to the laboratory in refrigerated polythene or glass containers filled with off-shore water. Low temperatures (2–9° C.) and darkness improved their chance of survival, and, after an initial 24-hr. recovery period, any surviving animals lived for a week to ten days.

During an experiment an animal lay on its side in a groove across the surface of a lucite disk. Silver–silver chloride gauze on the bottom of the groove served as the indifferent electrode. The groove was narrow enough to restrict movement without interfering with respiration. The plastic disk rested in a Petri dish containing just enough sea water to cover the animal in the groove. The Petri dish was surrounded by an ice bath.

The recording electrode was a piece of tungsten wire etched electrochemically to a tip of less than 2-μ diameter, and insulated down to near this tip with 'Insulex'. (The electrode was dipped in a diluted solution of 'Insulex', clamped with tip upward and dried rapidly in a gentle downward air current.) This microelectrode was attached to a

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plastic rod held in a ball-and-socket joint, such that the tip might penetrate the eye without blocking the light. Glass micropipettes with silver–silver chloride electrodes were used at first, but penetration of the eye with the tungsten electrodes seemed to give less damage as judged by survival time and gave identical electrical responses. The preparation was housed in a light-tight, copper-shielded box.

The light source, a 12-volt concentrated tungsten filament lamp, was situated outside the box, as were the filter holder and shutter, so that colour, intensity and duration of the stimulating flash could be altered without disturbing the preparation. The light entered the box through a baffled collimating tube, struck a concave mirror set at 45° across the light path, and was directed downward on to the exposed eye. Interference filters were used in the colour determinations, and the dimensions of the collimator were such that the useful 5° cone of these filters was not exceeded. A heavy-duty storage battery supplied power for the lamp, and the voltage across the lamp terminals was monitored throughout the experiments. Light intensity was varied with neutral density filters.

The inner surfaces of the lamp housing, filter holder, collimator and light-tight box were painted matt black.

Electrical signals from the recording electrode were fed via a cathode follower to a resistance-coupled amplifier and an ink writer or a cathode-ray oscilloscope. Control experiments were run to make sure that no artefact occurred due to photochemical properties of the electrode system. No electrical signals were detectable when the recording electrode was illuminated at the highest experimental intensity, whether simply immersed in sea water or inserted in the eye of a dead animal. Furthermore, in the absence of light on the eye, no electrical activity could be detected even when the animal exerted swimming movements.

At the outset of an experiment the room was darkened, the stimulating lamp was turned on, the shutter was opened and a deep red filter was placed in the light path. The animal was transferred quickly from the dark storage vessel to the indifferent electrode. The position of the Petri dish was adjusted such that only the eye of the subject was illuminated, and the recording electrode was inserted. The shutter and the door of the light-tight box were then closed, and the animal remained in total darkness for at least 30 min. before measurements were begun.

The response to a brief flash (100 msec.) of 'white' light of moderate intensity is shown in Fig. 1, with representative curves from (*A*) *Euphausia pacifica*, (*B*) *Nematoscelis difficilis* and (*C*) *Meganyctiphanes norvegica*. The response in each species is rapid, with a small *a*-wave lasting about 20 msec., a main response which reaches a peak in 40–50 msec., and a final overshoot in the other direction. Over a defined range of intensities the height of the main response to short flashes of light varies directly with the logarithm of the intensity of the light. At very low intensities the signal is lost in the noise, and at high intensities the signal reaches a limiting value, of the order of 200–300 μvolts.

Light flashes of longer duration induce an electrical response at both on and off (Fig. 1 *D*).

Preliminary studies of response to light of various wave-lengths have been made, both for equal biological response and for equal energy of illumination. The euphausiid eye is most sensitive to blue-green light ; but the spectral sensitivity curve does not coincide exactly with the spectral absorption curve of euphausiopsin, the light-sensitive pigment reported from the eyes of *Euphausia pacifica*[1].

The work on *E. pacifica* and *N. difficilis* was done at the Scripps Institution of Oceanography. The work on *M. norvegica* was done at The Laboratory, Plymouth. We should like to thank Dr. F. S. Russell, of Plymouth, and Dr. Harold Barnes, of Millport, for making the latter possible.

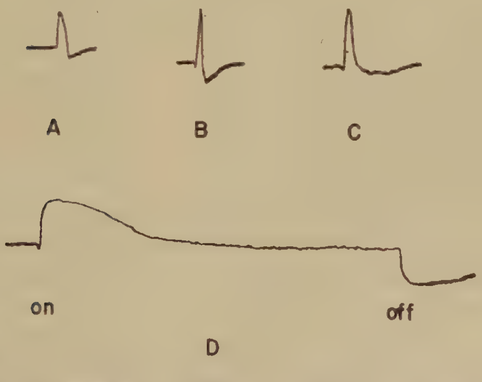

Fig. 1. Response to a 100-msec. flash of 'white' light by: (*A*) *Euphausia pacifica* (recorded with a cathode-ray oscilloscope); (*B*) *Nematoscelis difficilis* (recorded with a Beck–Lee ink writer); (*C*) *Meganyctiphanes norvegica* (recorded with an electro-encephalograph designed by Dr. Grey Walter); (*D*) response of *M. norvegica* to a 5-sec. flash

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[1] Kampa, E. M., *Nature*, **175**, 996 (1955).

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Abstract: *Twenty-one species of Radiolaria, ten of them new, are investigated in seventeen Oligocene and Lower Miocene samples from the Caribbean and tropical Pacific regions. It is possible to correlate sediments from the two regions approximately, on the basis of their radiolarian assemblages. Two series of species believed to show evolutionary sequences are discussed.*

Oligocene and Lower Miocene Radiolaria in tropical Pacific sediments

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INTRODUCTION

Investigation of the Radiolaria in sediment cores collected in the western tropical Pacific by the Swedish Deep-Sea Expedition showed the possibility of using these microfossils for approximate age-determinations of Tertiary and Quaternary sediments (Riedel, 1957). The author has recently examined more samples of Tertiary sediments collected from the Pacific floor by oceanographic expeditions of the University of California, Scripps Institution of Oceanography, and it now appears that the Radiolaria can be used to date sediments more precisely than the previous classification into early, middle and late Tertiary. The objects of this paper are to report some species that have been found useful in correlating Pacific sediments with each other and with those of the middle Tertiary of the Caribbean region, and to clarify the taxonomy of the species so used. The general geological and paleoceanographic implications of these stratigraphic studies of Pacific sediment cores will not be discussed at this time.

The Pacific sediments on which this study is principally based are all from within the tropics, and their Oligocene and Lower Miocene radiolarian assemblages are more analogous to those of the Caribbean region than to any assemblages that the author has examined from North America or Europe. For that reason, correlations are made with Caribbean stratigraphic units, namely those described by Bolli (1957) from the Cipero formation of Trinidad, and those described by Beckmann (1954) from the Oceanic formation of Barbados. For the purposes of this paper, the Eocene–Oligocene and Oligocene–Miocene boundaries as defined by Beckmann in Barbados and by Bolli in Trinidad, respectively, are accepted. Samples from Haiti and Trinidad now considered to be Lower Miocene in age were previously (Riedel, 1954, 1957) regarded as Oligocene, in accordance with an earlier view then prevailing.

Only a small part of the Cipero formation (Bolli's *Globigerinatella insueta* zone and *Globorotalia fohsi barisanensis* zone) has yielded well-preserved Radiolaria, and therefore, in order to expand the basis of Pacific Middle Tertiary radiolarian stratigraphy, it is necessary to use as reference samples some Pacific sediments that can be dated by their foraminiferal assemblages. Frances L. Parker has determined the following correlations of Middle Tertiary Pacific sediments, based on pelagic foraminifera: The lower part of Chubasco core 24 is approximately equivalent to Bolli's *Globorotalia fohsi barisanensis* zone; the lower part of Chubasco core 15 approximates his *Catapsydrax stainforthi* zone; Chubasco core 38 approximates his *Catapsydrax dissimilis* zone; and Chubasco core 17 approximates his *Globorotalia kugleri* zone. These correlations are based on a very small number of pelagic species, on the assumption that their ranges in the tropical Pacific are similar to those in Trinidad. The correlations agree in a general way with determinations made earlrie by M. N. Bramlette (personal communication) on the basis of the coccolithophorids. The author is grateful to these workers for the correlations indicated above, without which it would be impossible to relate the Middle Tertiary Pacific stratigraphy to a well known section exposed on land. It must be emphasized, however, that these correlations are only approximate. It would be foolhardy at present to state that any Pacific

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micropaleontology, vol. 5, no. 3, pp. 285–302, pls. 1–3, text-figs. 1–3, tables 1–2, july, 1959

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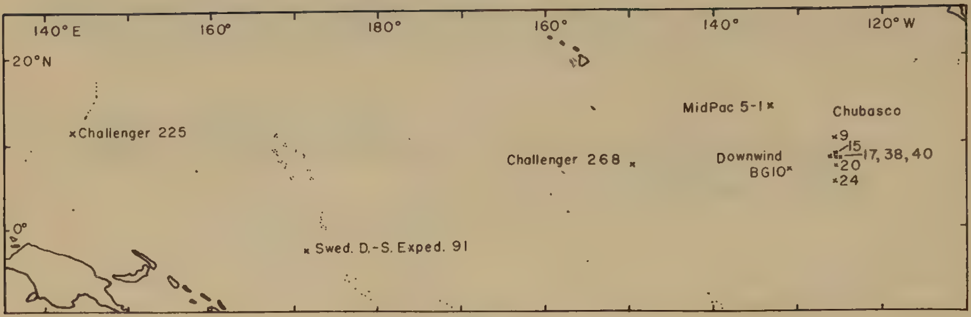


TEXT-FIGURE 1

LOCATIONS OF THE PACIFIC SAMPLES

sediment is of exactly the same age as a given zone of the Cipero formation, because of the short apparent duration of Bolli's zones and the considerable distance between the two areas involved.

For their ready assistance in supplying some of the samples on which this study is based, the author is grateful to P. Bronnimann, H. H. Renz, J. B. Saunders, and J. D. H. Wiseman. This paper is based in part on results of research carried out under contract with the U. S. Office of Naval Research.

Types and figured specimens will be deposited in the collections of the U. S. National Museum, Washington, D. C.

MATERIAL STUDIED

The localities of the Pacific and Caribbean samples used in this study are listed below. Tertiary material has been encountered in sediment cores at many localities in the tropical Pacific; those listed below contain well preserved Oligocene and Lower Miocene Radiolaria. The positions of the Pacific samples are indicated in text-figure 1.

Challenger (1875) Station 225: Lat. 11°24′ N., long. 143°16′ E.; depth 8180 meters.

Challenger (1875) Station 268: Lat. 7°35′ N., long. 149°49′ W.; depth 5500 meters.

Chubasco Expedition, Core 9, 96–98 cm. below top of core: Lat. 10°19′ N., long. 125°27′ W.; depth 4545 meters.

Chubasco Expedition, Core 15, 78–82 cm. below top of core: Lat. 8°31′ N., long. 125°25′ W.; depth 4462 meters.

Chubasco Expedition, Core 17, 11–15 cm. below top of core. Lat. 8°05′ N., long. 125°25′ W.; depth 4453 meters.

Chubasco Expedition, Core 20, 36–40 cm. below top of core: Lat. 7°22′ N., long. 125°30′ W.; depth 4549 meters.

Chubasco Expedition, Core 24, 16–20 cm. below top of core: Lat. 5°29′ N., long. 125°29′ W.; depth 4530 meters.

Chubasco Expedition, Core 38, 11–15 cm. below top of core: Lat. 8°12′ N., long. 125°19′ W.; depth 4315 meters.

Chubasco Expedition, Core 40, 16–20 cm. below top of core: Lat. 8°06′ N., long. 125°26′ W.; depth 4415 meters.

Downwind Expedition, Core BG 10, 13–15 cm. below top of core: Lat. 6°54′ N., long. 131°00′ W.; depth 4340 meters.

MidPac Expedition, Core 5–1, 26–27 cm. below top of core: Lat. 14°22′ N., long. 133°07′ W.; depth 4700 meters.

Swedish Deep-Sea Expedition, Core 91, 409–410 cm. and 1409–1410 cm. below top of core: Lat. 2°50′ S., long. 171°18′ E.; depth 4096 meters.

Globorotalia fohsi barisanensis zone of the Cipero formation: Dumfries Road, Palmiste Estate, near San Fernando, Trinidad, B.W.I.; TTOC no. 193123 (Bo. 200).

Globigerinatella insueta zone of the Cipero formation: Golconda Railway Station, near San Fernando, Trinidad, B. W. I.; TTOC no. 178697 (K. 9391).

TABLE 1

	Zones of Bolli (1957)	Reference samples	Approximate correlations based on Radiolaria
Lower Miocene	*Globorotalia fohsi barisanensis* zone, Cipero formation	*approx.* Chubasco core 24, 16–20 cm.	
		—— Dumfries Road, Trinidad (TTOC 193123)	—— Chubasco core 40, 16–20 cm.
			—— Chubasco core 9, 96–98 cm.
			—— Swed. D.-S. Exped. core 91, 409–410 cm.
	Globigerinatella insueta zone, Cipero formation	—— Golconda Railway Station, Trinidad (TTOC 178697)	—— *Challenger* Sta. 268
			—— Swed. D.-S. Exped. core 91, 1409–1410 cm.
			—— *Challenger* Sta. 225
			—— Chubasco core 20, 36–40 cm.
	Catapsydrax stainforthi zone, Cipero formation	*approx.* Chubasco core 15, 78–82 cm.	
			—— Seacliff at Jeremie, Haiti.
	Catapsydrax dissimilis zone, Cipero formation	*approx.* Chubasco core 38, 11–15 cm.	—— Downwind core BG 10, 13–15cm.
Oligocene Upper	*Globorotalia kugleri* zone, Cipero formation	*approx.* Chubasco core 17, 11–15 cm.	
Oligocene Lower	"Obere Bath Schichten" of Beckmann (1954), Oceanic formation	—— Upper part of Oceanic fm., Bath, Barbados	—— MidPac core 5-1, 26–27 cm.

Lower Miocene chalky marl from the sea cliff along the highway $^1/_2$ mile southeast of the plaza in Jeremie, Haiti; coll. W. P. Woodring; U.S.G.S. diatom loc. 3044.

"Obere Bath Schichten," near the top of the exposed section of the Oceanic formation at Bath, northwest of Conset Bay, Barbados; considered to be Lower Oligocene by Beckmann (1954).

STRATIGRAPHIC CORRELATIONS

Table 1 shows the samples used as references, dated on the basis of calcareous microfossils, and the correlations of other samples with these, based on the Radiolaria. The distributions of the radiolarian species in all samples are summarized in Table 2. The samples listed in these tables may not be in exactly chronological order, the sequence being based primarily on similarities and differences between the radiolarian assemblages. Local variations in ecological conditions are probably responsible for some of the characteristics of the various assemblages. Table 2 indicates that the Radiolaria, at least in that part of the tropical region under consideration, are useful in the stratigraphic correlation of Oligocene and Lower Miocene sediments over considerable geographic distances. Most of the species listed apparently have rather short time-ranges, and a number of them are common to Caribbean and tropical Pacific sediments.

SYSTEMATIC DESCRIPTIONS

Genus PIPETTELLA Haeckel, 1887

(Syn. *Pipetta* Haeckel, 1887)

Pipettella prismatica Haeckel
Plate 1, figure 1

Pipettella prismatica HAECKEL, 1887, Challenger Rept., Zool., vol. 18, pt. 1, p. 305, pl. 39, fig. 6.
Pipetta tuba HAECKEL, 1887, ibid., pp. 337–338, pl. 39, fig. 7.

Description: Cortical shell ellipsoidal, with the major axis generally 1.1–1.2 times the length of the minor axis, and with the wall somewhat thicker at the equa-

(525)

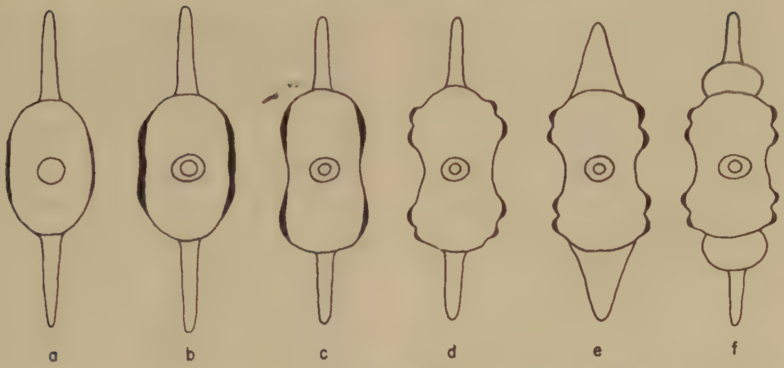
TABLE 2

	Trigonactura? angusta	*Tristylospyris triceros*	*Theocyrtis tuberosa*	*Artophormis gracilis*	*Cantharospyris ateuchus*	*Hexaspyris papilio*	*Phormocyrtis annosa*	*Lychnocanium bipes*	*Pipettella prismatica*	*Pipettaria tubaria*	*Brachiospyris simplex*	*Stichocorys wolffii*	*Cannartus violina*	*Dipodospyris forcipata*	*Cyrtocapsa pyrum*	*Calocyclas virginis*	*Calocyclas costata*	*Cannartus mammiferus*	*Dorcadospyris dentata*	*Cannartus laticonus*	*Brachiospyris alata*
Chubasco core 24, 16–20 cm.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	R	—	—	—	C	R
Dumfries Road, Trinidad	—	—	—	—	—	—	—	—	—	—	—	—	R	—	R	R	C	R	—	R	R
Chubasco core 40, 16–20 cm.	—	—	—	—	—	—	—	—	—	—	—	—	—	R	R	A	A	?*	C	?*	—
Chubasco core 9, 96–98 cm.	—	—	—	—	—	—	—	—	—	—	—	—	R	C	R	C	A	?*	C	?*	—
Swed. D.-S. Exped. core 91, 409-410 cm.	—	—	—	—	—	—	—	?	—	R	—	R	C	R	C	C	C	R	C	—	—
Challenger Sta. 268	—	—	R	—	—	—	—	?	R	—	—	C	R	C	C	A	C	R	C	—	—
Golconda Railway Station, Trinidad	—	—	—	—	—	—	—	—	—	R	—	A	C	R	R	C	R	C	C	—	—
Swed. D.-S. Exped. core 91, 1409–1410 cm.	—	—	—	—	—	—	—	—	R	C	R	A	C	C	C	A	—	—	—	—	—
Challenger Sta. 225	—	—	—	—	—	—	—	R	R	R	C	A	R	—	R	C	R	R	—	—	—
Chubasco core 20, 36–40 cm.	—	—	—	—	—	—	—	—	C	C	—	A	R	C	C	A	—	—	—	—	—
Chubasco core 15, 78–82 cm.	—	—	—	—	R	—	—	C	R	R	C	—	—	—	R	C	—	—	—	—	—
Seacliff at Jeremie, Haiti	—	—	—	—	C	—	—	C	C	R	—	—	—	R	C	C	—	—	—	—	—
Downwind core BG 10, 13–15 cm.	—	—	—	C	C	C	A	C	R	R	—	—	—	C	—	—	—	—	—	—	—
Chubasco core 38, 11–15 cm.	—	—	—	C	C	C	C	C	C	C	—	—	R	—	—	—	—	—	—	—	—
Chubasco core 17, 11–15 cm.	—	—	—	R	C	C	A	C	C	R	—	—	—	R	—	—	—	—	—	—	—
MidPac core 5–1, 26–27 cm.	C	C	A	C	R	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
"Bath Schichten," Bath, Barbados	C	C	A	C	R	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

* Specimens with a cortical twin-shell resembling that of *Cannartus mammiferus* or *Cannartus laticonus* are present in these samples' but the radiolarian skeletons have undergone a certain amount of dissolution, and it is impossible to determine the form of the polar columns, if any were originally present. In the table, A signifies abundant; C, common; and R, rare, in relation to the total radiolarian assemblage.

torial band than at the poles. Pores of the cortical shell circular, regularly arranged and usually hexagonally framed, ten to fifteen on the half-equator, separated by rather narrow intervening bars. Surface of the cortical shell slightly rough. Medullary shell almost invariably present, spherical or slightly lenticularly compressed, thin-walled and with subcircular pores, joined to the cortical shell by an equatorial series of trabeculae. Subcylindrical spongy polar columns arise rather abruptly from the cortical shell, and have meshes much smaller than those of the cortical shell. In some specimens the meshes of the polar columns are longitudinally aligned, and four to six longitudinal ridges extend along their surface.

Dimensions (based on thirty specimens): Major axis of cortical shell 115–163μ, minor axis 108–148μ. Diameter of medullary shell 28–38μ. Length of polar columns 50–240μ; median breadth 12–35μ.



TEXT-FIGURE 2

Diagrams to illustrate the suggested phyletic sequence from *Pipettella* to the panartids: a, *Pipettella prismatica*; b, *Pipettaria tubaria*; c, *Cannartus violina*; d, *Cannartus mammiferus*; e, *Cannartus laticonus*; f, *Panarium penultimum* (late Tertiary).

Localities and stratigraphic range: *Challenger* Sta. 225; *Challenger* Sta. 268; Chubasco core 15, 78–82 cm.; Chubasco core 17, 11–15 cm.; Chubasco core 20, 36–40 cm.; Chubasco core 38, 11–15 cm.; Downwind core BG 10, 13–15 cm.; seacliff at Jeremie, Haiti; Swed. D.-S. Exped. core 91, 1409–1410 cm. below top. In the samples studied, this species ranges from the Upper Oligocene to that part of the Lower Miocene which Bolli has designated the *Globigerinatella insueta* zone.

Remarks: A search for Haeckel's *Pipettella prismatica* and *Pipetta tuba* at their type locality (the sediment sample collected at *Challenger* Station 225) yielded only three specimens, which showed characters intermediate between those described and figured by Haeckel for these two species; the two names are therefore synonymized. None of the specimens found by the present author at *Challenger* Station 225 showed any trace of an equatorial constriction; all three specimens found possessed a medullary shell; two of the three specimens had longitudinal ridges on the polar tubes, and these ridges were five or six in number. In two of the three specimens, the pores of the cortical shell were hexagonally framed, although this character had no constant relation to the presence or absence of longitudinal ridges on the polar tubes.

Retention of this species in the genus *Pipettella* is necessitated by Campbell's (1954) designation of *Pipettella prismatica* as the type species of that genus. The definition of the genus *Pipettella* must therefore be emended by the addition of a statement that "a medullary shell is present in some species, but may be absent in others." Thus, the genus *Pipetta* must be combined with *Pipettella*.

Evaluation of the relationship of *Pipettella prismatica* to various of Haeckel's species of *Cenellipsis*, *Druppula*, *Prunulum*, and *Pipettaria* is difficult because of the poor state of preservation of radiolarian shells in many Tertiary sediments. Partial dissolution of the shells results in reduction or disappearance of the polar columns and medullary shells, which are more delicate than the cortical shells. Many of Haeckel's species may be based on shells that have suffered varying degrees of dissolution, and their distinguishing characters may be a function of the state of preservation rather than of any fundamental differences.

Cannartiscus canavarii and *Pipettella fallax*, which Vinassa (1900) described from the Italian Miocene, may be closely related to or identical with *Pipettella prismatica*; resolution of this question must await re-examination of topotype material.

Genus PIPETTARIA Haeckel, 1887

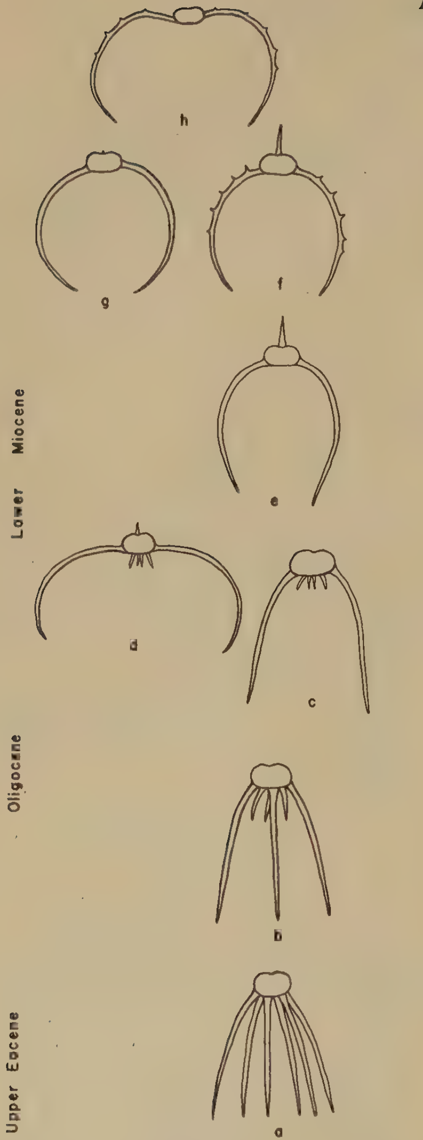
Pipettaria tubaria Haeckel

Plate 1, figure 2

Pipettaria tubaria HAECKEL, 1887, *Challenger* Rept., Zool., vol. 18, pt. 1, p. 339, pl. 39, fig. 15.

Description: Cortical shell usually rather thick-walled, ellipsoidal with an equatorial constriction, with pores subcircular, irregular in size and arrangement, eleven to eighteen on the half-equator. At the equatorial constriction the shell wall is puckered to form coarse plicae, which Haeckel called "short conical protuberances." At each pole arises a subcylindrical spongy column with meshes much smaller than those of the cortical shell. Medullary shells two (perhaps only one in some specimens), of which the outer is spherical or lenticularly compressed.

Dimensions (based on thirty specimens): Length of polar columns 63–125μ; median breadth 15–30μ. Length of cortical shell 108–145μ; maximum breadth 80–123μ. Breadth of outer medullary shell 33–40μ.



TEXT-FIGURE 3

Diagrams illustrating the approximate times of maximum development of some zygospyrids: a, generalized hexaspyrid, cf. *Hexaspyris buetschlii*; b, *Tristylospyris triceros*; c, *Cantharospyris ateuchus*; d, *Hexaspyris papilio*; e, *Dipodospyris forcipata*; f, *Dorcadospyris dentata*; g, *Brachiospyris simplex*; h, *Brachiospyris alata*.

Localities and stratigraphic range: Challenger Sta. 225; Chubasco core 15, 78–82 cm.; Chubasco core 17, 11–15 cm.; Chubasco core 20, 36–40 cm.; Chubasco core 38, 11–15 cm.; Downwind core BG 10, 13–15 cm.; Swed. D.-S. Exped. core 91, 409–410 cm. and 1409–1410 cm.; *Globigerinatella insueta* zone of the Cipero formation, Trinidad; seacliff at Jeremie, Haiti. This species apparently arose in the Upper Oligocene and ranged through a considerable part of the Lower Miocene, approximately up to Bolli's *Globigerinatella insueta* zone.

Remarks: With the object of checking on the range of variation of *Pipettaria tubaria*, the author searched through a considerable number of Radiolaria from its type locality, the sediment sample from *Challenger* Station 265. No specimens belonging to this species were found in that material. The Radiolaria at that locality were found to be a mixture of Quaternary and Tertiary forms, but most of the reworked Tertiary specimens are Eocene, and only a very few are Oligocene or Lower Miocene. Thus, *Pipettaria tubaria* is apparently very rare at its type locality.

Genus Cannartus Haeckel, 1882

(Syn. *Cannartidium* Haeckel, 1887)

Cannartus violina Haeckel
Plate 1, figure 3

Cannartus violina Haeckel, 1887, *Challenger* Rept., Zool., vol. 18, pt. 1, p. 358, pl. 39, fig. 10.

Cannartidium bicinctum Haeckel, 1887, ibid., p. 374, pl. 39, fig. 18.

Description: Cortical shell ellipsoidal, with an equatorial constriction and with pores subcircular or circular, twelve to eighteen on the half-equator. On the broader parts of the shell on either side of the equatorial constriction, the shell wall is somewhat thickened and puckered to form short, coarse plicae. At each pole arises a subcylindrical spongy column with meshes much smaller than those of the cortical shell. Medullary shells two, of which the inner is spherical and the outer spherical or lenticularly compressed. The thickened plicae, which are equatorial in *Pipettaria tubaria*, are situated on the two broad zones of the cortical twin-shell of *Cannartus violina*.

Dimensions (based on seventeen specimens): Length of polar columns 70–130μ; median breadth 15–33μ. Length of cortical shell 113–143μ; maximum breadth 85–108μ. Breadth of outer medullary shell 33–38μ.

Localities and stratigraphic range: Challenger Sta. 225; *Challenger* Sta. 268; Chubasco core 9, 96–98 cm.; Chubasco core 20, 36–40 cm.; Chubasco core 38, 11–15 cm.; Swed. D.-S. Exped. core 91, 409–410 cm. and 1409–1410 cm.; *Globorotalia fohsi barisanensis* and *Globigerinatella insueta* zones of the Cipero formation, Trinidad.

This species apparently arose at about the beginning of the Miocene, and ranged upward to that part of the Lower Miocene represented by Bolli's *Globorotalia fohsi barisanensis* zone. Of the localities listed, it was found most commonly in sediments believed to be approximately equivalent to Bolli's *Globigerinatella insueta* zone.

Remarks: With the object of determining whether *Cannartus violina* consistently possesses no medullary shells, the author searched through a considerable number of Radiolaria from the type locality of that species, the sediment collected at *Challenger* Station 268. Four specimens were found, of which one had no structures inside the cortical shell, one had only a series of centripetal equatorial trabeculae, and two had medullary shells exactly as Haeckel described in *Cannartidium bicinctum*. It appears that well preserved and completely developed specimens possess the medullary structures, which are absent in some specimens due to partial dissolution of the siliceous shells. Thus *Cannartidium bicinctum* is synonymized with *Cannartus violina*, and as the latter species has been designated as the type of its genus (Campbell, 1954), *Cannartidium* becomes synonymous with *Cannartus*; the two genera can no longer be distinguished on the basis of the presence or absence of medullary shells.

The Radiolaria that Haeckel described from *Challenger* Station 332, the type locality of his *Cannartidium bicinctum*, may well include Tertiary species. The present author has not had an opportunity to examine material from that locality, but several of the forms described from there by Haeckel are reported also to occur as fossils in Barbados.

The form which Martin (1904) identified from the Calvert formation of Maryland as *Cannartiscus amphicylindricus* Haeckel, and that which Nakaseko (1955) described from the Japanese Miocene as *Cannartidium amphicylindricum*, may both be identical with *Cannartus violina*, but this question cannot be resolved at present, because neither author gives any indication as to whether or not any parts of the twin-shell are relatively thickened.

Cannartus mammiferus (Haeckel)
Plate 1, figure 4

Cannartidium mammiferum Haeckel, 1887, *Challenger* Rept., Zool., vol. 18, pt. 1, p. 375, pl. 39, fig. 16. – Riedel, 1954, Deep-Sea Research, vol. 1, p. 172, pl. 1, fig. 1.

Description: Cortical shell ellipsoidal, with an equatorial constriction and with pores subcircular or circular, twelve to fifteen on the half-equator. On the broader parts of the shell, on either side of the equatorial constriction, there are pronounced obtuse moundlike protuberances, at which the shell wall is thickened. At each pole of the cortical shell arises a subcylindrical spongy column with meshes much smaller than those of the cortical shell. Medullary shells two, of which the inner is spherical and the outer spherical or lenticularly compressed. This species differs from *Cannartus violina* in that the protuberances on the cortical shell are mammilliform rather than pliciform.

Dimensions (based on twenty specimens): Length of polar columns 43–75μ; median breadth 20–30μ. Length of cortical shell 110–145μ; maximum breadth 93–115μ. Breadth of outer medullary shell 33–43μ.

Localities and stratigraphic range. – *Challenger* Sta. 225; *Challenger* Sta. 268; Swed. D.-S. Exped. core 91, 409–410 cm.; *Globigerinatella insueta* and *Globorotalia fohsi barisanensis* zones of the Cipero formation, Trinidad. This species has not been found in sediments older than Miocene, and ranges upward to that part of the Lower Miocene represented by Bolli's *Globorotalia fohsi barisanensis* zone.

Remarks: The description given above introduces some emendations to the definition of this species. In 1954 the author pointed out that specimens from *Challenger* Station 225 do not agree with the original description of *Cannartidium mammiferum*, in that the polar projections are spongy columns rather than hollow fenestrated tubes, and that the protuberances on the cortical twin-shell are less regular in form and arrangement than indicated by Haeckel. It is now possible, by examination of topotypic material, to determine that specimens from the type locality also possess these characters.

Cannartus laticonus Riedel, **new species**
Plate 1, figure 5

Description: Cortical twin-shell rather thick-walled, with pores subcircular or circular, ten to thirteen on the half-equator. On the broader parts of the shell, on either side of the equatorial constriction, are pronounced obtuse moundlike protuberances, at which the shell wall is thickened; there is a tendency in some specimens for these protuberances to be so arranged that two girdles of them encircle each half of the twin-shell. At each pole of the shell arises a broadly subconical, densely spongy column, which is almost as broad at its base as the polar surface of the twin-shell. Medullary shells two (or perhaps only one in some specimens), of which the inner is spherical and the outer spherical or lenticularly compressed. This species is distinguished from all others of the genus by the broadly subconical polar columns.

Dimensions (based on twenty specimens): Length of polar columns 45–70μ; median breadth 28–40μ. Length of cortical shell 93–125μ; maximum breadth 68–113μ. Breadth of outer medullary shell 30–35μ.

Localities and stratigraphic range: Chubasco core 24, 16–20 cm.; *Globorotalia fohsi barisanensis* zone of the Cipero formation, Dumfries Road, Palmiste Estate, near San Fernando, Trinidad (locality of the holotype, U.S.N.M. no. 563355). This species may be restricted to a part of the Lower Miocene corresponding approximately to Bolli's *Globorotalia fohsi barisanensis* zone, or it may extend up into the Middle Miocene.

Remarks: This species is one of a remarkable series of forms which evidently arose in the Upper Oligocene and underwent rapid evolutionary changes during the Miocene. They apparently represent the phyletic connection between the genus *Pipettella*, in which an ellipsoidal cortical shell without equatorial constriction bears subcylindrical spongy polar columns, and the panartids, in which the equatorially constricted cortical shell bears latticed polar caps. It has previously been shown (Riedel, 1957) that a common late Tertiary panartid, *Panarium penultimum*, has distinct polar caps surmounted by spongy polar columns, and the author has pointed out that this species probably developed from a form having less conspicuous polar caps and wider terminal spongy columns. Text-figure 2 indicates diagrammatically a possible evolutionary sequence of these related forms.

Pipettella prismatica and *Pipettaria tubaria* are both present in the Upper Oligocene and range upward into the Lower Miocene. *Cannartus violina*, in which the thickened plicae are situated on the broader parts of the cortical twin-shell rather than at the equatorial constriction, reached its acme in assemblages correlated approximately with Bolli's *Globigerinatella insueta* zone. At about the same time *Cannartus mammiferus* arose, in which the plicae are replaced by mammilliform protuberances that persist in the late Tertiary *Panarium penultimum*. These protuberances may also be homologous with those of *Panartus avitus* Riedel (1953), from the late Tertiary of the island of Rotti, near Timor, a species that may have arisen by loss of polar columns from the well developed polar caps. In sediments corresponding approximately with Bolli's *Globorotalia fohsi barisanensis* zone, the spongy columns become broader and somewhat denser, and in rare specimens of *Cannartus laticonus* the base of each spongy column is slightly separated from the polar surface of the twin-shell, thus apparently foreshadowing the subsequent development of distinct polar caps.

Genus TRIGONACTURA Haeckel, 1882

Trigonactura? angusta Riedel, **new species**

Plate 1, figure 6

Description: Phacoid cortical shell approximately three times as broad as the medullary shell (when the latter is distinct), with eight to eleven subcircular to circular pores on its radius. Cortical shell in some specimens filled with spongy meshwork. Three arms not strictly chambered, but rather subcylindrical spongy columns, broader at the base and tapered distally. In rare specimens a spongy patagium, its outline parallel to that of the cortical shell, connects the bases of the arms. This species is distinguished from all others of the genus by its relatively narrow, subcylindrical arms.

Dimensions (based on twenty specimens): Diameter of cortical shell 108–145μ; of medullary shell (shadowy outline seen through cortical shell) 35–50μ. Length of arms 85–158μ; median breadth 18–28μ.

Localities and stratigraphic range: MidPac core 5–1, 26–27 cm. (locality of the holotype, U.S.N.M. no. 563356); "Bath Schichten," near the top of the exposed section of the Oceanic formation at Bath, Barbados. The few data available indicate that *Trigonactura? angusta* may be restricted to the Lower Oligocene.

Remarks: The placement of this species in the genus *Trigonactura* is indicated as doubtful because a patagium is present in some specimens, and the medullary shell is not constant in structure; it is rarely if ever a well defined "shell." The arms differ in form from those of any other described members of this genus or closely related genera, probably because they represent a degeneration of the usual larger arms.

Genus TRISTYLOSPYRIS Haeckel, 1887

Tristylospyris triceros (Ehrenberg)

Plate 1, figures 7–8

Ceratospyris triceros EHRENBERG, 1874, K. preuss. Akad. Wiss., Monatsber., Jahrg. 1873, p. 220. – EHRENBERG, 1876, ibid., Abh., Jahrg. 1875, pl. 21, fig. 5.

Tristylospyris triceros (Ehrenberg). – HAECKEL, 1887, *Challenger* Rept., Zool., vol. 18, pt. 2, p. 1033.

Description: Shell nut-shaped, tuberculate, thick-walled, with indistinct sagittal stricture, and with subcircular to circular pores without regular arrangement. Three primary feet robust, circular in section, curved, with convexity outward. Secondary feet, which are not developed in all specimens, are one to seven in number (usually three), of the same general form as the primary feet but smaller. Rarely a small apical horn is present. The few specimens that could be observed from the base were found to have three large and six small collar pores, such as Bütschli (1882) described for *Petalospyris argiscus* Ehrenberg, and the three primary feet correspond in position with the bars separating the three large pores.

Dimensions (based on thirty specimens): Length of shell 68–88μ; of primary feet 155–415μ, of secondary feet 18–105μ. Breadth of shell 88–105μ.

Localities and stratigraphic range: MidPac core 5–1, 26–27 cm.; Upper Eocene and Lower Oligocene parts of the Oceanic formation at Bath, Barbados. This species has been found only in the Upper Eocene and Lower Oligocene.

Remarks: The emended description of *Tristylospyris triceros* given above admits a much greater range of variation than Ehrenberg or Haeckel granted this species. It includes forms which Haeckel would have placed in the genera *Tripospyris*, *Tristylospyris*, *Hexaspyris*, *Cantharospyris*, *Petalospyris*, and *Gorgospyris*. However, the author considers it more realistic to admit such intraspecific variation than to adhere rigidly to Haeckel's system of classification of the zygospyrids (Triospyrididae of Campbell, 1954).

Genus Dipodospyris Haeckel, 1882

Dipodospyris forcipata Haeckel
Plate 1, figure 9

Dipodospyris forcipata Haeckel, 1887, *Challenger* Rept., Zool., vol. 18, pt. 2, p. 1037, pl. 85, fig. 1.

Dipodospyris forcipata Haeckel. – Riedel, 1957, Swedish Deep-Sea Exped. Rept., vol. 6, no. 3, p. 79, pl. 1, fig. 3.

Localities and stratigraphic range: Challenger Sta. 268; Chubasco core 9, 96–98 cm.; Chubasco core 17, 11–15 cm.; Chubasco core 20, 36–40 cm.; Chubasco core 40, 16–20 cm.; Downwind core BG 10, 13–15 cm.; Swed. D.-S. Exped. core 91, 409–410 cm. and 1409–1410 cm.; *Globigerinatella insueta* zone of the Cipero formation, Trinidad; seacliff at Jeremie, Haiti. This species apparently first appeared in the Upper Oligocene, and ranged through a considerable part of the Lower Miocene.

Genus Brachiospyris Haeckel, 1882

Brachiospyris simplex Riedel, **new species**
Plate 1, figure 10

Description: Shell nut-shaped or subglobular, thick-walled, with no sagittal stricture externally and with subcircular to circular pores separated by wide intervening bars. Two long feet, circular in section, proximally widely divergent and subsequently semicircularly curved to become convergent distally. The outer sides of the feet of some specimens bear small (4–8μ) conical spinules. The cephalis of some specimens bears a short, weak apical horn. This species is distinguished from all others of the genus by the long feet, which are semicircularly curved and generally simple in structure.

Dimensions (based on thirty specimens): Length of apical horn 3–13μ; of shell 58–75μ; of feet 235–620μ. Breadth of shell 70–95μ.

Localities and stratigraphic range: Challenger Sta. 225; Chubasco core 15, 78–82 cm. (locality of the holotype, U.S.N.M. no. 563360); Swed. D.-S. Exped. core 91, 1409–1410 cm.

This species has been found in only a few samples, from a portion of the Lower Miocene believed to correspond approximately to Bolli's *Catapsydrax stainforthi* zone and perhaps to part of his *Globigerinatella insueta* zone.

Brachiospyris alata Riedel, **new species**
Plate 1, figures 11–12

Description: Shell thick-walled, nut-shaped, tuberculate, with slight sagittal stricture externally and subcircular to circular pores irregularly arranged and separated by wide intervening bars. Two feet, circular in section, widely divergent, proximally at 180° or sometimes more, subsequently curved downward to a greater or lesser extent, in occasional specimens approximately semicircular. The outer edges of the feet of most specimens bear short conical spinules. This species is distinguished from all other members of the genus by the pronounced divergence of the feet and the tendency to the development of accessory spinules on the feet.

Dimensions (based on twenty specimens): Length of shell 58–68μ; of feet 285–930μ; of accessory spinules 3–13μ. Breadth of shell 68–78μ.

Localities and stratigraphic range: Chubasco core 24, 16–20 cm. (locality of the holotype, U.S.N.M. no. 563362); *Globorotalia fohsi barisanensis* zone of the Cipero formation, Dumfries Road, Palmiste Estate, near San Fernando, Trinidad. This species has been found at only two localities, Bolli's *Globorotalia fohsi barisanensis* zone and a Pacific sediment believed to be of approximately the same age as that zone.

Remarks: Judging from the data at present available, *Brachiospyris alata* is the last representative of a remarkable phyletic series of two-footed and three-footed zygospyrids (Triospyrididae according to Campbell, 1954) that arose during the Upper Eocene, attained their acme during the Oligocene and Lower Miocene, and apparently became extinct at approximately the end of the Lower Miocene or in the Middle Miocene. Although the species reported in this paper do not include all members of this zygospyrid group – some of Haeckel's species were not met with during the present study – it seems probable that most of the more common and widespread members are included here. The group includes *Tristylospyris triceros*, *Cantharospyris ateuchus*, *Hexaspyris papilio*, *Dipodospyris forcipata*, *Dorcadospyris dentata*, *Brachiospyris simplex*, and *Brachiospyris alata*. This series of forms, with an indication of the time of maximum development of each, is illustrated diagrammatically in text-figure 3.

During the Upper Eocene, *Tristylospyris triceros*, with three primary feet and usually with three less strongly developed secondary feet, arose apparently from a form in which six basal feet were equally developed, possibly *Hexaspyris bütschlii* Haeckel or a related species. During the Oligocene, species arose in which the number of primary feet was reduced from three to two, with retention of the secondary feet (*Cantharospyris ateuchus* and *Hexaspyris papilio*). Species in which the secondary feet had disappeared, leaving only two strongly developed primary feet, first appeared in the Upper Oligocene, and reached their maximum development during the Lower Miocene (*Dipodospyris forcipata* and *Brachiospyris simplex*). Late in the Lower Miocene species arose in which the two feet were ornamented by accessory spinules (*Dorcadospyris dentata* and *Brachiospyris alata*); these youngest species tend to have shells reduced in size, with relatively small, sparse pores. Although it is not yet possible to trace in detail the phylogenetic development of each of these species, there can be little doubt that the reduction in number of the primary feet, and the later development of accessory spinules, are evolutionary trends within this group of species.

These species with thick-walled, tuberculate, generally nut-shaped shells appear to form a genetically related group which cuts across the taxonomic boundaries set up in Haeckel's system. When sufficient data are available for a revision of Haeckel's system, this is the type of grouping of species on which genera should be based.

Genus Dorcadospyris Haeckel, 1882

Dorcadospyris dentata Haeckel
Plate 1, figure 13

Dorcadospyris dentata Haeckel, 1887, *Challenger* Rept., Zool., vol. 18, pt. 2, p. 1040, pl. 85, fig. 6. – Riedel, 1957, Swedish Deep-Sea Exped. Rept., vol. 6, no. 3, pp. 79–80, pl. 1, fig. 4.

Dorcadospyris decussata Haeckel, 1887, *Challenger* Rept., Zool., vol. 18, pt. 2, p. 1041, pl. 85, fig. 7.

Localities and stratigraphic range: Challenger Sta. 268; Chubasco core 9, 96–98 cm.; Chubasco core 40, 16–20 cm.; Swed. D.-S. Exped. core 91, 409–410 cm.; *Globigerinatella insueta* zone of the Cipero formation, Trinidad.

This species has been found only in sediments from a part of the Lower Miocene corresponding approximately to Bolli's *Globigerinatella insueta* zone. Thus, the author's earlier speculation (Riedel, 1957, p. 75) that the appearance of *Dorcadospyris dentata* subsequent to that of *Dipodospyris forcipata* might represent a useful stratigraphic marker is apparently confirmed.

Genus Hexaspyris Haeckel, 1887

Hexaspyris papilio Riedel, **new species**
Plate 2, figures 1–2

Description: Shell nut-shaped, tuberculate, thick-walled, with no sagittal stricture externally and with subcircular to circular pores without regular arrangement. Two primary feet more strongly developed than the others, circular in section, initially divergent at approximately 180° or more, then curved semicircularly and thus convergent terminally. Secondary feet three to eight in number (often four), lamellar or subcylindrical, varying in form and disposition. A stout, conical apical horn is present in most specimens. This species is distinguished from all others of the genus by the two primary feet, which are extremely divergent.

Dimensions (based on twenty-five specimens): Length of apical horn 65–245μ; of shell 63–88μ; of primary feet 260–880μ; of secondary feet 25–340μ. Breadth of shell 83–100μ.

Localities and stratigraphic range: Chubasco core 17, 11–15 cm.; Chubasco core 38, 11–15 cm. (locality of the holotype, U.S.N.M. no. 563364); Downwind core BG 10, 13–15 cm. This species has been found in only a few sediments of Upper Oligocene and lowermost Miocene age.

Remarks: Although the total number of feet in this species ranges up to ten, its placement in the genus *Hexaspyris* is based on the frequent occurrence of four secondary and two primary feet.

Genus Cantharospyris Haeckel, 1887

Cantharospyris ateuchus (Ehrenberg)
Plate 2, figures 3–4

Ceratospyris ateuchus Ehrenberg, 1874, K. preuss. Akad. Wiss., Monatsber., Jahrg. 1873, p. 218. – Ehrenberg, 1876, ibid., Abh., Jahrg. 1875, pl. 21, fig. 4.

Cantharospyris ateuchus (Ehrenberg). – Haeckel, 1887, *Challenger* Rept., Zool., vol. 18, pt. 2, p. 1051.

Description: Shell nut-shaped, tuberculate, thick-walled, with indistinct sagittal stricture and with subcircular to circular pores without regular arrangement. Two primary feet robust, circular in section, usually tending to be straight, though in some specimens curved, with convexity outward. Secondary feet not present in all specimens, one to four in number, much smaller than the primary feet. In some specimens a small amount of irregular lamellar meshwork is developed in place of the secondary feet. In many specimens a small apical horn is present. The one specimen that could be observed from the base was found to have three large and six small collar pores, similar to those of *Tristylospyris triceros*, and the primary spines correspond in position with the bars which Bütschli (1882) designated as *e* in his figure of the collar structures of *Petalospyris argiscus* Ehrenberg.

Dimensions (based on thirty specimens): Length of shell 63–98μ; of primary feet 190–720μ; of secondary feet 20–188μ. Breadth of shell 78–120μ.

Localities and stratigraphic range: Chubasco core 15, 78–82 cm.; Chubasco core 17, 11–15 cm.; Chubasco core 38, 11–15 cm.; Downwind core BG 10, 13–15 cm.; MidPac core 5–1, 26–27 cm.; seacliff at Jeremie, Haiti; "Bath Schichten," Oceanic formation, Bath, Barbados. This species occurs rarely in the Lower Oligocene part of the Oceanic formation at Bath, Barbados and in MidPac core 5–1, and is common in Haitian and Pacific sediments believed to be Upper Oligocene and lowermost Miocene in age.

Remarks: It seems advisable to retain the generic name *Cantharospyris* instead of following the suggestion of Campbell (1954) to use the name *Platybursa* for this genus, until some decision is made as to the application of the Principle of Conservation, at present under review by the International Commission on Zoological Nomenclature. This species may be closely related to that described from the Italian Langhian as *Cantharospyris tuberculatus* by Carnevale (1908).

Genus Lychnocanium Ehrenberg, 1847

Lychnocanium bipes Riedel, **new species**
Plate 2, figures 5–6

Description: Cephalis globular, hyaline or with a few reduced pores, and bearing a conical or weakly clavate apical horn. Thorax inflated hemispherical, with thick wall, slightly rough surface, and circular pores quincuncially arranged. From the base of the thorax arise two heavy, generally divergent, three-bladed feet, which are to a greater or lesser extent curved, with convexity outward. Mouth somewhat narrower than widest part of thorax. In some specimens, a rudimentary subcylindrical abdomen is developed between the feet. This species is distinguished from all others of the genus by having only two feet.

Dimensions (based on thirty specimens): Length of apical horn 8–55μ; of cephalis 23–33μ; of thorax 76–115μ; of feet 125–275μ. Maximum breadth of thorax 100–145μ.

Localities and stratigraphic range.—Challenger Sta. 225; doubtfully at *Challenger* Sta. 268; Chubasco core 15, 78–82 cm.; Chubasco core 17, 11–15 cm.; Chubasco core 38, 11–15 cm. (locality of the holotype, U.S.N.M. no. 563369); Downwind core BG 10, 11–15 cm.; doubtfully in Swed. D.-S. Exped. core 91, 409–410 cm.; sea-cliff at Jeremie, Haiti.

This species is apparently restricted to the Upper Oligocene and lowermost Miocene. The doubtful occurrences (rare, broken specimens) at *Challenger* Sta. 268 and in Swed. D.-S. Exped. core 91 at 409–410 cm. may be due to reworking of older material into younger sediments.

Remarks: Lychnocanium bipes is an aberrant species, unique among its relatives in possessing only two feet. The constancy of their structure, and their occurrence in large numbers at some localities, indicate that the two-footed specimens are not teratological.

If this species is accepted as belonging to the genus *Lychnocanium*, the following emendations must be made to higher taxonomic categories:

Genus *Lychnocanium* Ehrenberg, 1847: Tripocyrtida (or Sethopiliidae) with shell mouth open, and with three *or rarely two* solid terminal feet on the peristome. No thoracic ribs. Cephalis with a horn.

Family Tripocyrtida Haeckel, 1887 (Sethopiliidae according to Campbell, 1954): Cyrtoidea with two-jointed shell, divided by a transverse constriction into cephalis and thorax, and bearing three *or rarely two* radial apophyses.

Stöhr (1880, pp. 106–107, pl. 4, figs. 14–15) described two species from the Sicilian Miocene, *Pterocanium bibrachiatum* and *Pterocanium falciferum*, as having only two basal feet. Haeckel (1887, p. 1317) grouped these two species together as *Pterocorys falcifera* (Stöhr), and considered that this species normally has three feet. The present author has searched through the Radiolaria from several localities of the Sicilian "tripoli" (from Grotte, from near Serradifalco, and from near Raddusa), and has found no dicyrtid with only two feet.

Genus Phormocyrtis Haeckel, 1887

Phormocyrtis annosa Riedel, **new species**
Plate 2, figure 7

Description: Cephalis elongate, lobate, with a few small pores, surmounted by a stout three-bladed horn. Thorax inflated-campanulate, with regular circular pores. Thoracic wall pronouncedly plicate longitudinally, the plicae being separated by three to five longitudinal rows of pores. Abdomen subcylindrical, with a thinner wall than the thorax, and subcircular to circular pores usually less regularly arranged than in the thorax. In most specimens the thoracic plicae extend into the abdomen, where they become less distinct. Termination of the abdomen usually ragged, but in some specimens with approximately eight to fifteen parallel, triangular lamellar feet or teeth. This species differs from all others of the genus in having a thick-walled, pronouncedly plicate thorax.

Dimensions (based on thirty specimens): Length of apical horn 68–120μ; of cephalis 30–45μ; of thorax 108–138μ; of abdomen 38–143μ. Maximum breadth (usually at thorax) 130–173μ.

Localities and stratigraphic range: Chubasco core 17, 11–15 cm. (locality of the holotype, U.S.N.M. no. 563370); Chubasco core 38, 11–15 cm.; Downwind core BG 10, 13–15 cm. The only sediments in which this species has been found are believed to be Upper Oligocene and lowermost Miocene in age.

Remarks: The structure of the cephalis of *Phormocyrtis annosa* is apparently similar to that described in *Anthocyrtidium cineraria* Haeckel and *Calocyclas virginis* Haeckel (Riedel, 1957, pp. 84–86 and 90–93).

Genus Calocyclas Ehrenberg, 1847

Calocyclas virginis Haeckel
Plate 2, figure 8

Calocyclas virginis Haeckel, 1887, *Challenger* Rept., Zool., vol. 18, pt. 2, pp. 1381–1382. – Riedel, 1957 (part), Swedish Deep-Sea Exped., Rept., vol. 6, no. 3, pp. 90–92, pl. 4, figs. 3–4 (not fig. 5); text-fig. 5.

Calocyclas sp., Jacob and Shrivastava, 1952, Science and Culture, vol. 17, pp. 346–348, text-fig. 2.

Description: Cephalis ovate, lobed, with usually sparse subcircular to circular pores, and bearing a stout apical horn which is usually conical but rarely weakly three-bladed. Thorax subspherical, with roughened surface. Thoracic pores circular, usually regularly hexagonally arranged, often with a tendency toward apparent longitudinal alignment, rarely with the longitudinal rows separated by long ridges. Usually no lumbar stricture externally. Abdomen subcylindrical or tapering distally, narrower than the widest part of the thorax. Abdominal pores subcircular or circular, usually smaller than those of the thorax, in most specimens longitudinally aligned. Terminal feet eleven to sixteen, lamellar, usually truncate, parallel, broader than the spaces between them, usually situated opposite alternate rows of abdominal pores.

Dimensions (based on thirty specimens): Length of apical horn 30–140μ; of cephalis 35–40μ; of thorax 65–130μ; of abdomen 20–90μ; of feet 10–45μ. Breadth of cephalis 33–43μ; of thorax 98–175μ; of abdomen (distally) 78–100μ.

Localities and stratigraphic range: Challenger Sta. 225; *Challenger* Sta. 268; Chubasco core 9, 96–98 cm.; Chubasco core 15, 78–82 cm.; Chubasco core 20, 36–40 cm.; Chubasco core 24, 16–20 cm.; Chubasco core 40, 16–20 cm.; Swed. D.-S. Exped. core 91, 409–410 cm. and 1409–1410 cm.; *Globorotalia fohsi barisanensis* and *Globigerinatella insueta* zones of the Cipero formation, Trinidad; seacliff at Jeremie, Haiti. This species ranges throughout that part of the Lower Miocene under consideration in this paper, with the exception of those sediment samples that are believed to be approximately equivalent to Bolli's *Catapsydrax dissimilis* zone.

Remarks: The description of this species given above is somewhat narrower than that given earlier (Riedel, 1957). This more precise definition is made possible by an examination of specimens from a greater number of localities, which shows the advisability of separating pronouncedly costate individuals as a separate species (see below).

Calocyclas costata Riedel, **new species**
Plate 2, figure 9

Calocyclas virginis Haeckel. – Riedel, 1957 (part), Swedish Deep-Sea Exped., Rept., vol. 6, no. 3, pp. 90–92, pl. 4, fig. 5 (not figs. 3–4).

Description: Cephalis ovate, lobed, with sparse subcircular to circular pores and bearing a stout, conical apical horn. Thorax subspherical, with pores circular, hexagonally arranged and with a pronounced tendency to longitudinal alignment, the longitudinal rows separated by pronounced costae. No lumbar stricture externally. Abdomen subcylindrical or tapering distally, narrower than the widest part of the thorax. Abdominal pores subcircular or circular, arranged hexagonally with apparent longitudinal alignment (these longitudinal lines are continuous with those of the thorax) and often with longitudinal ridges separating pore rows. Terminal feet eleven to eighteen in number, lamellar, usually truncate, parallel or slightly convergent,

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PLATE 1

1 *Pipettella prismatica* Haeckel
Chubasco core 38, 11–15 cm.; × 210; U.S.N.M. no. 563351.

2 *Pipettaria tubaria* Haeckel
Chubasco core 20, 36–40 cm.; × 210; U.S.N.M. no. 563352.

3 *Cannartus violina* Haeckel
Globigerinatella insueta zone of the Cipero formation, Golconda Railway Station, Trinidad; × 210; U.S.N.M. no. 563353.

4 *Cannartus mammiferus* (Haeckel)
Globigerinatella insueta zone of the Cipero formation, Golconda Railway Station, Trinidad; × 210; U.S.N.M. no. 563354.

5 *Cannartus laticonus* Riedel, n. sp.
Holotype, × 210; U.S.N.M. no. 563355; *Globorotalia fohsi barisanensis* zone of the Cipero formation, Dumfries Road, Palmiste Estate, Trinidad.

6 *Trigonactura? angusta* Riedel, n. sp.
Holotype, × 185; U.S.N.M. no. 563356; MidPac core 5-1, 26–27 cm.

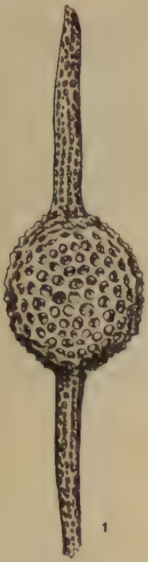
7–8 *Tristylospyris triceros* (Ehrenberg)
MidPac core 5-1, 26–27 cm.; × 100: 7, U.S.N.M. no. 563357; 8, U.S.N.M. no. 563358.

9 *Dipodospyris forcipata* Haeckel
Chubasco core 20, 36–40 cm.; × 100; U.S.N.M. no. 563359.

10 *Brachiospyris simplex* Riedel, n. sp.
Holotype, × 100; U.S.N.M. no. 563360; Chubasco core 15, 78–82 cm.

11–12 *Brachiospyris alata* Riedel, n. sp.
Chubasco core 24, 16–20 cm.; × 100; 11, U.S.N.M. no. 563361; 12, holotype, U.S.N.M. no. 563362.

13 *Dorcadospyris dentata* Haeckel
Chubasco core 9, 92–96 cm.; × 100; U.S.N.M. no. 563363.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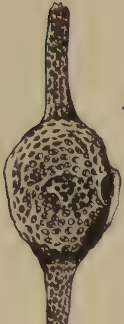
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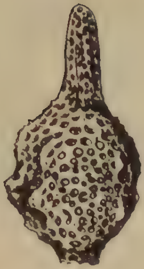
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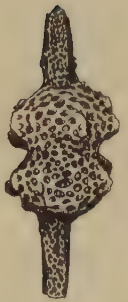
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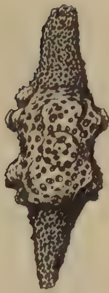
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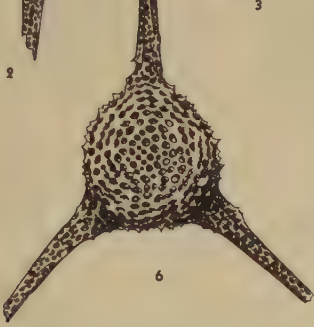
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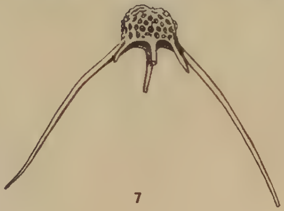
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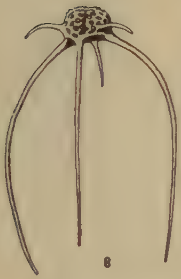
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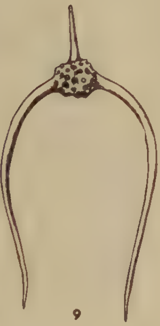
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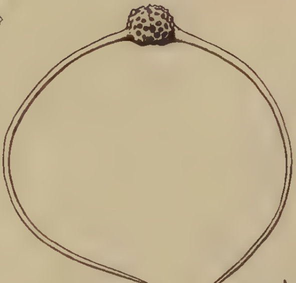
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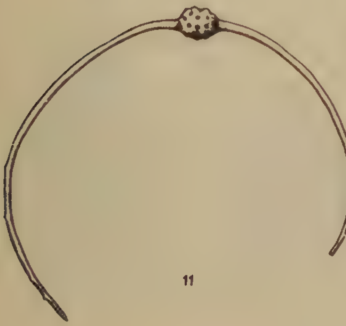
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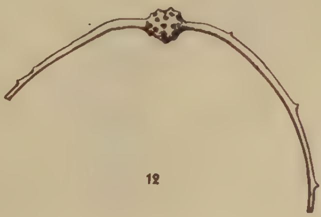
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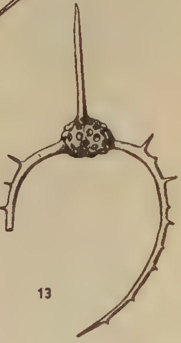
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broader than the spaces between them, usually situated opposite alternate rows of abdominal pores. This species is distinguished from *Calocyclas virginis* by the pronouncedly costate thorax and otherwise smooth shell surface.

Dimensions (based on thirty specimens): Length of apical horn 115–230μ; of cephalis 30–45μ; of thorax 70–100μ; of abdomen 10–33μ; of feet 12–70μ. Breadth of cephalis 38–53μ; of thorax 103–135μ; of abdomen (distally) 75–108μ.

Localities and stratigraphic range: Challenger Sta. 225; *Challenger* Sta. 268; Chubasco core 9, 96–98 cm.; Chubasco core 40, 16–20 cm.; Swed. D.-S. Exped. core 91, 409–410 cm.; *Globorotalia fohsi barisanensis* zone (locality of the holotype, U.S.N.M. no. 563372) and *Globigerinatella insueta* zone of the Cipero formation, Trinidad.

This species has been found only in sediments from that part of the Lower Miocene corresponding approximately to Bolli's *Globorotalia fohsi barisanensis* and *Globigerinatella insueta* zones.

Remarks: Although rare specimens appear to be transitional between *Calocyclas virginis* and *Calocyclas costata*, it is now considered advisable to recognize the two as distinct species. Transitional forms are to be expected if *Calocyclas costata* arose from *Calocyclas virginis*, as appears to have been the case.

Genus Theocyrtis Haeckel, 1887

Theocyrtis tuberosa Riedel, **new species**
Plate 2, figures 10–11

Description: Cephalis elongate, subdivided into three(?) indistinct loculi, with rough surface and subcircular to

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PLATE 2

1 *Hexaspyris papilio* Riedel, n. sp.
Chubasco core 17, 11–15 cm.; × 90; U.S.N.M. no. 563364.

2 *Hexaspyris papilio* Riedel, n. sp.
Holotype, × 100; U.S.N.M. no. 563365; Chubasco core 38, 11–15 cm.

3 *Cantharospyris ateuchus* (Ehrenberg)
Chubasco core 38, 11–15 cm.; × 100; U.S.N.M. no. 563366.

4 *Cantharospyris ateuchus* (Ehrenberg)
Chubasco core 17, 11–15 cm.; × 100; U.S.N.M. no. 563367.

5 *Lychnocanium bipes* Riedel, n. sp.
Chubasco core 17, 11–15 cm.; × 185; U.S.N.M. no. 563368.

6 *Lychnocanium bipes* Riedel, n. sp.
Holotype, × 185; U.S.N.M. no. 563369; Chubasco core 38, 11–15 cm.

7 *Phormocyrtis annosa* Riedel, n. sp.
Holotype, × 185; U.S.N.M. no. 563370; Chubasco core 17, 11–15 cm.

8 *Calocyclas virginis* Haeckel
Chubasco core 20, 36–40 cm.; × 210; U.S.N.M. no. 563371.

9 *Calocyclas costata* Riedel, n. sp.
Holotype, × 210; U.S.N.M. no. 563372; *Globorotalia fohsi barisanensis* zone of the Cipero formation, Dumfries Road, Palmiste Estate, Trinidad.

10 *Theocyrtis tuberosa* Riedel, n. sp.
"Obere Bath Schichten" of the Oceanic formation at Bath, Bardabos; × 210; U.S.N.M. no. 563373.

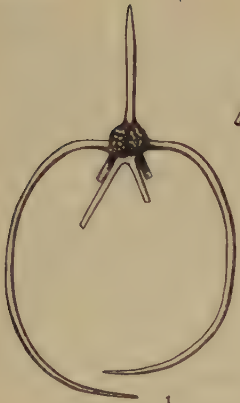
11 *Theocyrtis tuberosa* Riedel, n. sp.
Holotype, × 210; U.S.N.M. no. 563374; MidPac core 5–1, 26–27 cm.

12 *Artophormis gracilis* Riedel, n. sp.
Holotype, × 210; U.S.N.M. no. 563375; Chubasco core 17, 11–15 cm.

13 *Artophormis gracilis* Riedel, n. sp.
Chubasco core 38, 11–15 cm.; × 210; U.S.N.M. no. 563376.

14 *Stichocorys wolffii* Haeckel
Globigerinatella insueta zone of the Cipero formation, Golconda Railway Station, Trinidad; × 210; U.S.N.M. no. 563377.

15 *Cyrtocapsa pyrum* Haeckel
Chubasco core 20, 36–40 cm.; × 210; U.S.N.M. no. 563378.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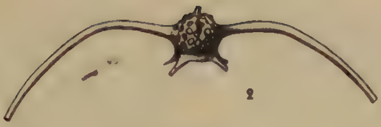
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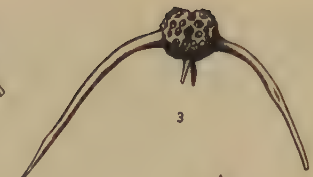
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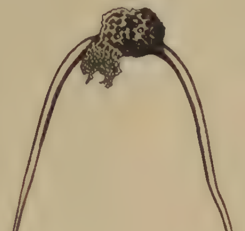
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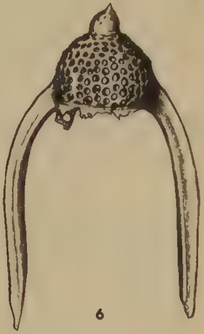
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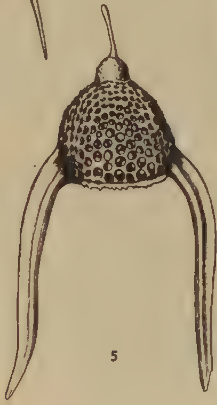
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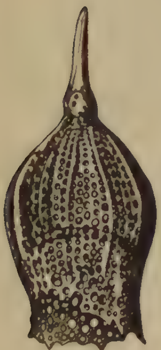
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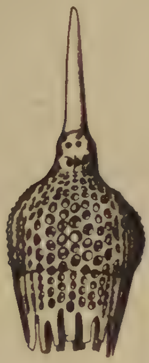
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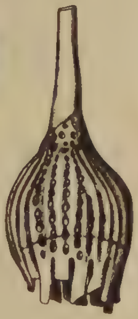
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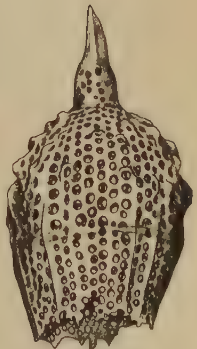
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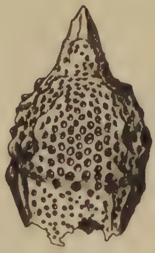
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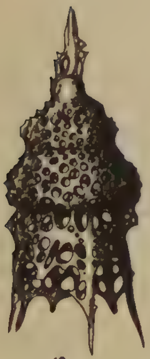
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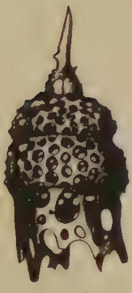
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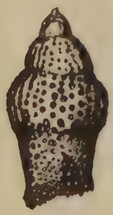
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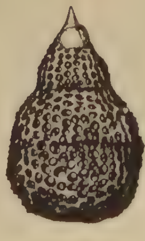
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circular pores. Apical horn short, stout, three-bladed, often irregular in form or forked. Thorax subhemispherical, with pronouncedly tuberose surface due to low irregular protuberances, and subcircular to circular pores showing a tendency to longitudinal alignment. Lumbar stricture indistinct externally. Abdomen subcylindrical, somewhat contracted distally, usually with ragged termination, and having a plicate wall in which adjacent plicae are separated by two to four longitudinal rows of subcircular to circular pores. This species is distinguished from all others of the genus by the tuberose surface of the thoracic wall.

Dimensions (based on thirty specimens): Length of apical horn 13–50µ; of cephalis 28–50µ; of thorax 83–133µ; of abdomen 38–168µ. Breadth of cephalis 35–45µ; of thorax 120–175µ.

Localities and stratigraphic range: MidPac core 5-1, 26–27 cm. (locality of the holotype, U.S.N.M. no. 563374); "Bath Schichten," Oceanic formation, Bath, Barbados. Rare specimens found in the sediment from *Challenger* Sta. 268 may be a result of reworking of older Radiolaria into a younger sediment. The few data now available indicate that this species may be restricted to the Lower Oligocene.

Remarks: In order to determine whether or not this species might be similar to *Theocyrtis ptychodes* Haeckel (1887, p. 1408, pl. 69, fig. 8), the author searched through a large number of Radiolaria from the original sediment sample collected at *Challenger* Station 272, the type locality of that species. No form was found that resembled *Theocyrtis ptychodes*, indicating that it must be very rare if present at that locality. The structure of the cephalis of *Theocyrtis tuberosa* is apparently similar to that described in *Anthocyrtidium cineraria* Haeckel and *Calocyclas virginis* Haeckel (Riedel, 1957).

Genus ARTOPHORMIS Haeckel, 1882

Artophormis gracilis Riedel, **new species**
Plate 2, figures 12–13

Description: Shell conical above, subcylindrical below, consisting of four segments separated by moderately distinct strictures. Cephalis globular, hyaline or with a few small pores, bearing an apical spine, which may be simple conical, multiple, or latticed. Thorax truncate-conical and abdomen inflated annular, both of these segments rather thick-walled, with rough surface and pores subcircular or circular, irregular in size and arrangement. Fourth segment consisting essentially of four to twenty longitudinal ribs joined together by a rather delicate lamellar meshwork with irregular pores; the longitudinal ribs terminate in free spines, and in some specimens are not clearly distinguishable from the meshwork.

This species differs from *Artophormis barbadensis* (Ehrenberg, 1874, pp. 217–218; 1876, pl. 18, fig. 8: Haeckel, 1887, p. 1459), which occurs in the Eocene part of the Oceanic formation of Barbados, in having a more inflated third segment, and in the greater differentiation of the fourth segment from the third.

Dimensions (based on thirty specimens): Length of apical horn 3–63µ; of cephalis 20–30µ; of thorax 38–58µ; of abdomen 43–78µ; of fourth segment (including terminal spines) 25–145µ. Maximum breadth (at third or fourth segment) 95–145µ.

Localities and stratigraphic range: Chubasco core 17, 11–15 cm. (locality of the holotype, U.S.N.M. no. 563375); Chubasco core 38, 11–15 cm.; Downwind core BG 10, 13–15 cm.; MidPac core 5-1, 26–27 cm.; "Bath Schichten," Oceanic formation, Bath, Barbados. This species apparently ranges from the Lower Oligocene to the lowermost Miocene.

Genus STICHOCORYS Haeckel, 1882

Stichocorys wolffii Haeckel
Plate 2, figure 4

Stichocorys wolffii HAECKEL, 1887, *Challenger* Rept., Zool., vol. 18, pt. 2, p. 1479, pl. 80, fig. 10. – RIEDEL, 1957, Swedish Deep-Sea Exped., Rept., vol. 6, no. 3, pp. 92–93, pl. 4, figs. 6–7.

Stichocorys baerii HAECKEL, 1887, *Challenger* Rept., Zool., vol. 18, pt. 2, pp. 1479–1480, pl. 80, fig. 8.

Localities and stratigraphic range: Challenger Sta. 225; *Challenger* Sta. 268; Chubasco core 20, 36–40 cm.; Swed. D.-S. Exped. core 91, 409–410 cm. and 1409–1410 cm.; *Globigerinatella insueta* zone of the Cipero formation, Trinidad. This species has been found only in sediments from a part of the Lower Miocene believed to correspond approximately to Bolli's *Globigerinatella insueta* zone.

Genus CYRTOCAPSA Haeckel, 1882

Cyrtocapsa pyrum Haeckel
Plate 2, figure 15

Cyrtocapsa pyrum HAECKEL, 1887, *Challenger* Rept., Zool., vol. 18, pt. 2, p. 1513, pl. 78, fig. 8.

Cyrtocapsa cornuta HAECKEL, 1887, ibid., p. 1513, pl. 78, fig. 9.

Description: Shell rough, thick-walled, approximately pear-shaped, consisting of four segments, of which the third or fourth is broadest. The collar stricture and that between the third and fourth segments are not pronounced, but the stricture between the thorax and the third segment is distinct, and marks a change in the contour of the shell. Cephalis small, subspherical, often bearing a conical horn. Thorax and third segment approximately campanulate or annular. Fourth segment hemispherical or cap-like, often with a large terminal pore representing the much reduced mouth. Pores circular or subcircular, separated by narrow intervening bars.

Dimensions (based on thirty specimens): Total length of shell 175–200µ; maximum breadth 115–140µ. Length of apical horn 5–20μ; of cephalis 18–26μ; of thorax 30–45μ; of third segment 50–70μ; of fourth segment 42–75μ.

Localities and stratigraphic range: Challenger Sta. 225; *Challenger* Sta. 268; Chubasco core 9, 96–98 cm.; Chubasco core 15, 78–82 cm.; Chubasco core 20, 36–40 cm.; Chubasco core 24, 16–20 cm.; Chubasco core 40, 16–20 cm.; Swed. D.-S. Exped. core 91, 409–410 cm. and 1409–1410 cm.; *Globigerinatella insueta* and *Globorotalia fohsi barisanensis* zones of the Cipero formation, Trinidad; seacliff at Jeremie, Haiti. This species apparently arose in the Lower Miocene and ranged upward at least as far as Bolli's *Globorotalia fohsi barisanensis* zone and probably higher.

Remarks: The decision to place *Cyrtocapsa cornuta* in synonymy with *Cyrtocapsa pyrum* is based on a re-examination of specimens from the type localities of the two species (*Challenger* Stations 272 and 268, respectively). *Cyrtocapsa cornuta* is rather common in the sediment from Station 268, and exhibits all transitions between Haeckel's descriptions and figures of the two species. The Radiolaria in the sediment sample from Station 272 are predominantly Quaternary in age but include a small proportion of admixed Eocene, Lower Miocene, and possibly Pliocene species. A search through a large number of the Radiolaria from this locality yielded one complete and three broken *Cyrtocapsa* skeletons, which do not differ significantly from the species at Station 268.

In order to check on the identity of *Cyrtocapsa compacta* Haeckel, a portion of the original sediment sample from its type locality (*Challenger* Station 206) was also re-examined. The Radiolaria in that sample all appear to be Quaternary in age, and no form resembling *Cyrtocapsa compacta* was found.

The presence of a large terminal pore on the fourth segment, apparently representing a constricted mouth, raises the question of whether or not *Cyrtocapsa pyrum* ought more properly to be placed in the genus *Eucyrtidium.* However, because this species does not appear to be closely related to *Eucyrtidium acuminatum*, which Frizzell and Middour (1951, p. 33) designated as the type species of that genus, it is considered advisable to leave it in the genus *Cyrtocapsa.* Tan Sin Hok (1927, p. 28) has pointed out that the classification of cyrtids as "aperta" or "clausa" cannot always be strictly applied. Haeckel's description of *Cyrtocapsa* as having the terminal mouth "closed by a lattice-plate" is here somewhat misleading, as the terminal closure is effected by constriction of the mouth, and not by the development of a separate lattice-plate over the mouth.

Determination of the true relationships and stratigraphic ranges of species of *Cyrtocapsa* is complicated by the apparently independent development of superficially similar forms during different geologic periods. For example, it is not unlikely that *Cyrtocapsa pyrum* is genetically related to the species which Vinassa (1900) described from the Italian Miocene, but it appears highly improbable that these Miocene forms are truly related to the Mesozoic species of *Cyrtocapsa* and *Stichocapsa* described by Tan Sin Hok (1927). The present author is aware of no similar forms in the lower Tertiary.

BIBLIOGRAPHY

BECKMANN, J. P.
1954 – *Die Foraminiferen der Oceanic Formation (Eocaen-Oligocaen) von Barbados, Kl. Antillen.* Eclogae Geol. Helv., vol. 46 (1953), no. 2, pp. 301–412, pls. 16–30, text-figs. 1–29, table 1.

BOLLI, H. M.
1957 – *Planktonic foraminifera from the Oligocene-Miocene Cipero and Lengua formations of Trinidad, B.W.I.* In: LOEBLICH, A. R., JR., AND OTHERS, U. S. Nat. Mus., Bull., no. 215, pp. 97–123, pls. 22–29, text-figs. 17–21.

BÜTSCHLI, O.
1882 – *Beiträge zur Kenntnis der Radiolarienskelette, insbesondere der der Cyrtida.* Zeitschr. Wiss. Zool., vol. 36, pp. 485–540, pls. 31–33.

CAMPBELL, A. S.
1954 – *Radiolaria.* In: CAMPBELL, A. S., AND MOORE, R. C., *Treatise on invertebrate paleontology.* New York and Lawrence: Geol. Soc. Amer. and Univ. Kansas Press, Part D (Protista 3), pp. 11–163, text-figs. 6–86.

CARNEVALE, P.
1908 – *Radiolarie e silicoflagellati di Bergonzano (Reggio Emilia).* R. Ist. Veneto Sci. Lettere Arti, Mem., vol. 28, no. 3, pp. 1–46, pls. 1–4.

EHRENBERG, C. G.
1874 – *Grössere Felsproben des Polycystinen-Mergels von Barbados mit weiteren Erläuterungen.* K. Preuss. Akad. Wiss., Monatsber., Jahrg. 1873, pp. 213–263.
1876 – *Fortsetzung der mikrogeologischen Studien als Gesammt-Uebersicht der mikroskopischen Paläontologie gleichartig analysirter Gebirgsarten der Erde, mit specieller Rücksicht auf den Polycystinen-Mergel von Barbados.* K. Preuss. Akad. Wiss., Abh., Jahrg. 1875, pp. 1–226, pls. 1–30.

FRIZZELL, D. L., AND MIDDOUR, E. S.
1951 – *Paleocene Radiolaria from southeastern Missouri.* Missouri, Univ., School Mines, Bull., Tech. Ser., no. 77, 41 pp., 3 pls.

HAECKEL, E.
1887 – *Report on the Radiolaria collected by H. M. S. Challenger during the years 1873–76.* Challenger Exped. 1873–1876, Rept., Zool., vol. 18, clxxxviii + 1803 pp., 140 pls.

JACOB, K., AND SHRIVASTAVA, R. N.
1952 – *Fossil Radiolaria and Silicoflagellata from the Tertiary clays of Colebrooke Island and the Ritchie's Archipelago, Andaman Islands.* Science and Culture, vol. 17, no. 8, pp. 346–348.

MARTIN, G. C.
1904 – *Radiolaria.* Maryland, Geol. Survey, Miocene, pp. 447–459, pl. 130.

NAKASEKO, K.
1955 – *Miocene radiolarian fossil assemblage from the southern Toyama Prefecture in Japan.* Osaka Univ., Sci. Repts., no. 4, pp. 65–127, pls. 1–11.

RIEDEL, W. R.

1953 – *Mesozoic and late Tertiary Radiolaria of Rotti.* Jour. Pal., vol. 27, no. 6, pp. 805–813, pls. 84–85.

1954 – *The age of the sediment collected at Challenger (1875) Station 225 and the distribution of Ethmodiscus rex (Rattray).* Deep-Dea Research, vol. 1, pp. 170–175, pl. 1.

1957 – *Radiolaria: a preliminary stratigraphy.* Swedish Deep-Sea Exped., Rept., vol. 6, no. 3, pp. 61–96, pls. 1–4.

STÖHR, E.

1880 – *Die Radiolarienfauna der Tripoli von Grotte, Provinz Girgenti in Sicilien.* Palaeontographica, vol. 26 (ser. 3, vol. 2), pp. 69–124, pls. 1–7.

TAN SIN HOK

1927 – *Over de samenstelling en het ontstaan van krijt- en mergelgesteenten van de Molukken.* Netherlands Indies, Jaarb. Mijnw., Verh., Jaarg. 55 (1926), pp. 1–165, pls. 1–16.

VINASSA DE REGNY, P.

1900 – *Radiolarie miocenici italiani.* R. Accad. Sci. Ist. Bologna, Mem. Sci. Nat., ser. 5, vol. 8, pp. 565–595, pls. 1–3.

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Venom of the lionfish Pterois volitans[1, 2]

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SAUNDERS, PAUL R. AND PETER B. TAYLOR. *Venom of the lionfish Pterois volitans*. Am. J. Physiol. 197(2): 437–440. 1959.—Extracts prepared from the venomous dorsal spines of lionfish (*Pterois volitans*) were investigated in mice and rabbits. Intravenous injection into mice produced death in from less than a minute up to about one-half hour. The primary action in rabbits was a fall in blood pressure, accompanied by increase in respiratory rate; with larger doses there was evidence of myocardial ischemia or injury. After injection of fatal doses a variety of electrocardiographic changes occurred and the blood pressure fell to zero; respiratory arrest occurred terminally, but artificial respiration did not prolong the life of the animal. The active material was nondialyzable and the extracts contained considerable amounts of protein. Extracts retained substantial activity after lyophilization or addition of glycerol when stored for over a year at −20°C. The mean LD_{50} following intravenous injection into mice was about 1 mg of protein/kg.

FISHES OF THE GENUS *Pterois* (family *Scorpaenidae*) have been known for many years to be capable of inflicting extremely painful and sometimes serious wounds through stings by the venomous spines (1–5). Species of *Pterois* are distributed chiefly in shallow-water over wide areas of the tropical Indo-Pacific, and are often found in underwater caves or swimming about slowly in regions of rock or coral formations. These fishes present a spectacular appearance, with brilliant distinctive markings and long delicate fins, and are known by a variety of common names such as 'lionfish,' 'turkeyfish,' and 'zebrafish.'

Wounds have occurred chiefly in fishermen and swimmers as a result of contact with the sharp spines, which readily penetrate the flesh (1). In addition to the pain immediately after the sting, marked swelling and inflammation soon occur at the site of the wound and may spread and involve the entire leg. Systemic poisoning may also occur, with severe fall in blood pressure (unpublished observation).

The venom apparatus of the dorsal, anal and pelvic spines of *Pterois volitans* (Linnaeus) has been described by Halstead *et al.* (2). The venom-producing tissue is located beneath the integumentary sheath of the spines; the sheath is ruptured when the spine penetrates the flesh of the victim, and the venom diffuses into the puncture wound.

A number of specimens of *Pterois volitans* (Linnaeus) have been collected, and some physiological and other properties of extracts prepared from the spines are described for the first time in this report.

MATERIALS AND METHODS

Collection of specimens. Specimens were collected at depths of 25 feet or less on the lagoon side of Parry Island at Eniwetok Atoll, Marshall Islands. They were captured alive by divers using hand nets made of chicken-wire; damage to the venomous spines by such nets was minimal, in contrast to our experience with nets made of twine. The fish were maintained alive in the aquarium until used. A total of 15 specimens (mean standard length 22 cm) were used in the work reported here.

Preparation of venom extracts. The fishes were killed by decapitation, and the 13 dorsal spines were cut free at the base. All subsequent manipulations were conducted at 1–5°C. The distal three-fourths of the integumentary sheath of each spine, together with the underlying glandular tissue within the anterolateral-glandular grooves (2) was scraped off into distilled water or 0.9% NaCl solution. The tissue was minced briefly with scissors, and then ground in an agate mortar in the presence of a small amount of clean sand. This initial extraction was carried out in 1.6 ml of water or saline per gm of spines (weighed immediately after removing spines and blotting them of excess water). Grinding was continued for a few minutes until a homogeneous suspension was obtained; the suspension was then centrifuged at about 500 × *g* for 5 minutes, and the insoluble fraction was re-extracted for several minutes with an

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additional 0.4 ml of water or saline per gm of spines. The latter suspension was centrifuged and the supernatant fraction combined with that from the first centrifugation.

The crude extracts thus obtained as somewhat turbid, reddish-orange solutions with a pH of approximately 7 were stored at 3°C prior to preservation of activity by other procedures (see RESULTS).

Bioassay in mice. Extracts prepared as described above were diluted with 0.9% NaCl solution (usually about 1:10) immediately prior to bioassay and injected intravenously into male albino mice (Webster Swiss strain, mean weight 22 gm) via a tail vein. The solution was injected over a period of about 5 seconds; the volumes injected did not exceed 0.2 ml. All animals were observed for a minimum of 48 hours after injection.

Recording of blood pressure, respiration and electrocardiogram in anesthetized rabbits. Albino rabbits (mean weight 2.2 kg) were anesthetized with 1–1.5 gm/kg of urethan administered intraperitoneally. Blood pressure was recorded from a carotid artery with a mercury manometer and respiration recorded by a lever attached to a thread sewn to the skin above the diaphragm. The trachea was cannulated in all experiments; artificial respiration by means of a pulmotor valve attached to a compressed air source was initiated after the onset of respiratory arrest in some experiments. Venom solutions were injected intravenously through a catheter into a jugular vein. Electrocardiograms were taken at a chart speed of 25 mm/sec. (1 mv equal to 10 mm deflection); changes were most definite in lead I, although lead III was also used in some experiments.

Chemical methods. Nitrogen was determined by the micro-Kjeldahl method (6). Protein was determined with the biuret reagent of Gornall *et al.* (7); a calibration curve was prepared with crystalline bovine albumin (Armour) over the range 0.5–2.0 mg of protein, and the samples were read at 540 mμ in a Bausch and Lomb Spectronic 20 colorimeter.

RESULTS

Acute toxicity in mice. Intravenous injection of venom killed animals in about 30 seconds to 30 minutes, depending upon the dose; animals which did not die within a half-hour usually survived indefinitely with no apparent ill-effects. Amounts of venom fatal in 2–10 minutes produced any or all of the following symptoms initially: ataxia, circling movements and partial or complete paralysis of legs. A period of inactivity usually followed, with evidence of muscular weakness (e.g. the head often rested on the floor of the cage unless the animal was prodded, in which case the mouse usually moved about slowly). This apparent skeletal muscular weakness was more pronounced with the venom of *Pterois volitans* than with the venoms of the stonefishes *Synanceja verrucosa*, Bloch and Schneider (8), and *Synanceja horrida* (Linnaeus) (unpublished observations). The effects in mice of all three of these venoms were similar in most other respects. Rolling or peddling movements (less violent in general than after the injection of stonefish venom) usually occurred terminally, and were followed immediately by respiratory arrest. The auricles and ventricles were usually still contracting when the chest was opened within a minute after respiratory arrest; the auricles usually were still beating with a regular rhythm. Approximately 2500 LD_{50} doses for mice were present in extracts prepared from the combined dorsal spines of each individual fish.

Venom extracts injected intraperitoneally were lethal at 5–10 times the intravenous LD_{50} dose. The mice became very inactive within a few minutes after the injection and when prodded to move displayed a slow ataxic gait which persisted until death, which occurred in 1–6 hours at the dosage levels used. Collapse, respiratory arrest and death were preceded by marked slowing of the respiration and intermittent twitching of the legs for a few minutes.

Extracts prepared in 0.9% NaCl from the skin adjacent to the dorsal spines (using the same ratio of volume of saline to weight of tissue as was used with the spines) were inactive in mice at doses 10 times as large as were lethal with extracts prepared from the spines (dose calculated on basis of weight of tissue used for extraction).

It was not possible to carry out protein analyses on freshly prepared extracts in the field. Subsequent analyses on stored glycerol-treated samples (after centrifuging and discarding the precipitate as described later) and on reconstituted lyophilized samples indicated a mean LD_{50} for four separate extracts of 1.1 mg of protein/kg. By the time at which the protein analyses were performed, these stored extracts had lost an average of 30% of their activity, by comparison with the freshly prepared extracts which had been bioassayed immediately after preparation.

Stability of venom under various conditions of storage. Freshly prepared extracts were treated as described below in

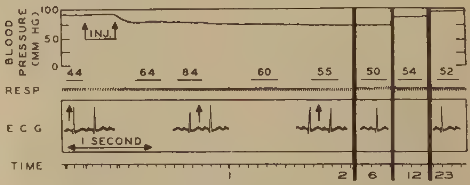

FIG. 1. Effect of small dose of venom of *Pterois volitans* on blood pressure, respiration and electrocardiogram of a rabbit. 130 μg of venom protein/kg was injected between arrows above. *Heavy vertical lines* indicate interruption of recording. *Numbers above record* of respiration indicate respiratory rate/min. during time interval denoted by horizontal lines beneath these numbers. *Signal marks* are at 5-sec. intervals, and *numbers below signal* marks show time (min.) after injection of venom. *Arrows* above ECG (lead I) denote point at which record taken; time scale for ECG is indicated by *horizontal arrow*. Inspiration appears as downward stroke on record of respiration.

order to maintain the potency of the venom during transport to the United States and subsequent storage.

Extracts were bioassayed in mice within one hour after preparation, the pH was adjusted to 7.5, and the extracts were then preserved either *a*) by lyophilization or *b*) by addition of glycerol (analytical reagent) to a final concentration of 40%. The lyophilized samples were stored subsequently in sealed glass vials *in vacuo* and the glycerol-treated samples in sealed glass vials in the presence of air. Samples were maintained for as long as 2 weeks at −20°C, then for 6 days packed in dry ice while being transported from Eniwetok to the United States. Subsequent storage has been at −20°C. A flocculent reddish-brown precipitate appeared in the glycerol-treated samples over a period of several weeks at −20°C; centrifugation yielded a clear, almost colorless supernatant solution and a precipitate (which was discarded). Little or no further precipitation occurred on further storage. Lyophilized samples were reconstituted with water to the original volume and centrifuged to give a clear supernatant solution and a small amount of reddish precipitate which was discarded. Such reconstituted samples usually lost about one-fourth of their activity on storage at 3°C for 24 hours.

Bioassays of representative lyophilized and glycerol-treated samples after about 1 year of storage has indicated that from 40 to 90% of the original activity was retained. Precise determination of the stability was not possible because of the limited number of mice (about 15) available in the field for bioassay of each freshly-prepared extract. It is clear, however, that substantial activity was retained on storage; furthermore, the symptoms produced in mice by stored extracts appeared identical with those produced by freshly prepared extracts.

Stability of the venom on storage of the spines themselves was also investigated. Spines from several fish, removed as described under MATERIALS AND METHODS, were sealed in polyethylene bags, which were then packed in dry ice for 6 days and stored subsequently at −20°C. Extracts prepared from these spines in the usual manner after storage for periods of up to 3 months were of comparable potency and produced in mice symptoms apparently identical to those evoked by extracts prepared from fresh spines.

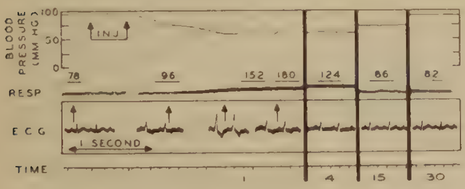

FIG. 2. Effect of moderate dose of venom of *Pterois volitans* on blood pressure, respiration, and electrocardiogram of a rabbit. 180 µg of venom protein/kg was injected between arrows above. Legend otherwise as in fig. 1.

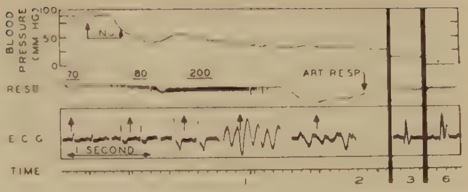

FIG. 3. Effect of fatal dose of venom of *Pterois volitans* on blood pressure, respiration and electrocardiogram of a rabbit. 200 µg of venom protein/kg was injected between arrows above. Artificial respiration started at arrow at rate of 62/min. Legend otherwise as in fig. 1.

Other properties of venom. Reconstituted lyophilized saline extracts were dialyzed in Visking cellulose casing at 2°C against 0.9% NaCl solution for 12–18 hours. Bioassay in mice of the contents of the dialysis tubing afterward indicated a potency identical with that of an undialyzed control sample.

Extracts prepared in deionized water were of comparable potency and produced in mice effects which appeared to be identical with those produced by extracts prepared in 0.9% NaCl solution.

The mean protein content (biuret) of extracts which had been stored for 6–12 months in 40% glycerol was determined after centrifuging and discarding the reddish-brown precipitate described above. The mean protein content (calculated for the original volume of extract prior to the addition of glycerol) was 0.29%. Lyophilized samples reconstituted to the original volume of the extract possessed a mean protein content of 0.55% and a mean nitrogen content of 0.095%.

Effect on blood pressure, respiratory rate and electrocardiogram of anesthetized rabbits. Both glycerol-treated and lyophilized extracts were used in these experiments, and identical results were obtained; the extracts used had been stored from 6 to 12 months after preparation from fresh material. There was no evidence of a cumulative effect or tachyphylaxis following repeated injection of small to moderate doses at intervals of about 30 minutes. Seventeen rabbits were used in the experiments reported here.

Minimal doses produced a slight fall in blood pressure accompanied by an increase in respiratory rate, with no effect upon the heart rate or electrocardiogram (fig. 1); these effects disappeared within about 20–30 minutes. Larger doses caused a more marked fall in blood pressure and increase in respiratory rate, with evidence of myocardial ischemia or injury (flattening or inversion of T wave, or displacement of the S-T segment), or conduction defects such as bundle branch block. Little or no change in cardiac rate occurred, and the effects disappeared within about 30 minutes (fig. 2). The blood pressure usually returned, after the first small or moderate dose administered to a given animal, to a value which was about 20% above the preinjection pressure, and this elevated pressure usually persisted for a half-hour or longer. Injection of fatal doses produced effects initially which were similar to those described above; a variety of additional electrocardiographic changes soon appeared (e.g. extrasystoles, bundle branch block, ventricular tachycardia, ventricular fibrillation). The respiration slowed and finally ceased, and the blood pressure continued to decrease (fig. 3). The auricles (and sometimes the ventricles) were usually still beating when the chest was opened within a minute or two after respiratory arrest; some irregular electrical activity in the heart usually persisted for an additional 5 minutes or more. Initiation of artificial respiration in eight animals within about one-half minute after respiratory arrest was ineffective in prolonging the life of the animal (fig. 3).

The mean lethal dose in the above experiments was approximately 200 μg protein/kg.

DISCUSSION

The authors are not aware of any well documented account of fatal poisoning from a wound by any species of *Pterois*. A near-fatal case occurred several years ago in the Marshall Islands following a sting by a specimen of *Pterois volitans* (unpublished observation), in which the victim's blood pressure fell to a very low value and death appeared imminent. However, epinephrine was administered intravenously, and the patient's heart rate and blood pressure soon began to return to normal; no permanent after-effects of the sting were noted.

The work reported here indicates that the primary action of the venom on the cardiovascular system is the production of a marked hypotension (together with an increased respiratory rate), with essentially no change in the electrocardiogram following small doses. Amounts of venom sufficient to lower the blood pressure to about one-half to two-thirds the preinjection value produced also evidence of myocardial ischemia or injury which was reversible if the animal recovered; cardiac rate changes were again minimal, but this of course may have been due to depression of cardiac reflexes by anesthesia. We have no evidence at present to indicate whether these effects on the electrocardiogram were due to a direct action on the myocardium or coronary vessels, or were secondary to the hypotension.

Respiratory arrest occurred as a terminal event; artificial respiration was ineffective in prolonging the life of the animal. Therapeutic measures directed toward the support of the circulation would appear to be indicated in the treatment of seriously poisoned victims, together with artificial respiration if needed.

The actions of the venom of *Pterois volitans* upon mice and upon the cardiovascular and respiratory systems of anesthetized rabbits appear very similar to those of the venoms of the stonefishes *Synanceja verrucosa* (8) and *Synanceja horrida* (unpublished observations). Mice appeared to suffer more from skeletal muscular weakness prior to death from lionfish venom, and in addition, the duration of action upon the cardiovascular system of rabbits was somewhat greater than with stonefish venoms. In other respects, however, the effects were essentially indistinguishable. Certain other properties of the venoms were also similar (e.g. their stability on storage under various conditions, and the nondialyzability of the active components). The common local effects (i.e. pain and swelling) seen in victims stung by *Pterois* and *Synanceja* also suggest the similar nature of the venoms. The apparently less dangerous consequences of most lionfish as compared to stonefish stings may reflect mainly a difference in the amount of venom entering the wound, rather than important differences in the nature of the venoms.

The active substance or substances in *Pterois* venom are nondialyzable; this fact, together with the presence of substantial amounts of proteins in the extracts, indicates that the active material is identical with or closely associated with protein.

The authors are grateful to the Scripps Institution of Oceanography, University of California and to Prof. D. L. Fox of that Institution for the use of facilities during much of this investigation. The assistance of Miss Joanne Prestwood in some of the animal experiments is also appreciated. We express our thanks to the U. S. Atomic Energy Commission for general assistance and the use of facilities of the Eniwetok Marine Biological Laboratory, Marshall Islands, and particular thanks to Mr. Walter Hughes and Mr. Kenneth Harpster, who captured most of the fish used in this work. All specimens were identified by Dr. D. W. Strasburg, Pacific Oceanic Fishery Investigations, Fish and Wildlife Service, U. S. Dept. of Interior, Honolulu, Hawaii; Dr. Strasburg's assistance is gratefully acknowledged.

REFERENCES

1. BOTTARD, A. *Les Poissons Venimeux*. Paris: Octave Doin, 1889, p. 164.
2. HALSTEAD, B. W., M. J. CHITWOOD AND F. R. MODGLIN. *Anat. Rec.* 122: 317, 1955.
3. RAY, C. AND C. W. COATES. *Copeia* 1958, p. 235.
4. SCHNEE. *Arch. Schiffs- u. Tropenhyg.* 12: 166, 1908.
5. PAWLOWSKY, E. N. *Gifttiere und ihre Giftigkeit*. Jena: Gustav Fischer, 1927, p. 121.
6. STEYERMARK, A. *Quantitative Organic Microanalysis*. New York: Blakiston, 1951, p. 140.
7. GORNALL, A. G., C. J. BARDAWILL AND M. M. DAVID. *J. Biol. Chem.* 177: 751, 1949.
8. SAUNDERS, P. R. *Science.* 129: 272, 1959.

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Albinism in the California Hagfish Eptatretus stoutii

Abstract. The discovery of an albino specimen of the hagfish, *Eptatretus stoutii* (Lockington), is reported, together with general notes regarding collection of this species for research purposes. The extreme abundance of hagfish in the area described refutes the generally accepted notion that they are of infrequent occurrence in southern California waters.

True albinism occurs but rarely among fishes, and it is believed that this is the first record of such a natural freak to be reported among the most primitive of craniate chordates, the hagfish (Fig. 1). There is a report of an albino lamprey (*Petromyzon marinus*), the other division of the class Cyclostomata, which was collected some years ago at the mouth of the Salmon River on Lake Champlain in New York (*1*).

During a routine collection for specimens of *Eptatretus stoutii* (= *Polistotrema stoutii*) on 5 May 1959, using 5-gallon-can traps, I obtained an albino individual in a total collection of some 500 fish. Over the past 2 years I have taken about 5900 hagfish of this species from the same general vicinity (latitude, 32° 31′N; longitude, 117° 18′W). This area is the floor of a submarine canyon, a tributary of the San Diego Trough, where the bottom is green mud and the depth is 210 fathoms. The traps remained on the bottom for 7 hours and they were baited with fish oil and mackerel.

Normally, the body color of this species is pinkish to purple grey, lighter ventrally than dorsally. Of the several thousand hagfish studied, about 20 were piebald (Fig. 2), with certain areas pale pink because of reduced pigmentation.

The skin of the albino is white save for a pinkish cast imparted by the blood. This coloration is most pronounced in the eye regions, the barbels, and the caudal area. The pulsations of the caudal heart are plainly visible beneath the translucent skin.

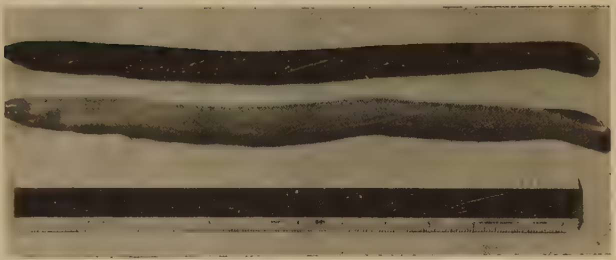

Fig. 1. Living albino *Eptatretus stoutii* with normally colored individual for comparison (anesthetized). Note the slime glands beneath the skin in the albino (especially prominent posterior to the gill openings), not readily evident in the pigmented specimen.

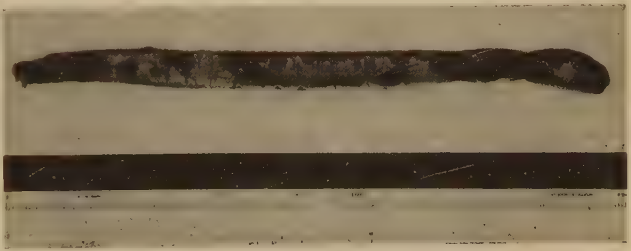

Fig. 2. Piebald specimen of *Eptatretus stoutii* (preserved), collected 7 Nov. 1958.

Measurements of the albino specimen (*2*) were as follows: body length, snout to tip of tail, 38.1 cm; weight, 55 g; external gill openings, 12 left, 12 right. Measurements of the piebald specimen were as follows: body length, 28.3 cm; weight, 36 g; gill openings, 11 left, 11 right.

DAVID JENSEN

Scripps Institution of Oceanography, University of California, La Jolla

References and Notes

1. F. H. Wilson, *Lebanon Valley College Alumni News* (January 1954).
2. This specimen was obtained during the course of research supported by a grant from the San Diego County Heart Association, to which grateful acknowledgment is made.

10 June 1959

Contributions from the Scripps Institution of Oceanography, New Series, 1098

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Zeitschrift für Physik, 154, 172—174 (1959)

From the Scripps Institution of Oceanography, University of California, La Jolla, Calif.

Increase of C^{14} in the Atmosphere from Artificial Sources Measured in a California Tree

By

GEORGE S. BIEN and H. E. SUESS

With 1 Figure in the text

(Eingegangen am 7. November 1958)

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An increase in atmospheric C^{14} from neutrons produced in atomic bomb testing was anticipated by WILLARD F. LIBBY in 1956[1]. Such increase has now been observed by a number of investigators. RAFTER and FERGUSSON[2] have measured the specific C^{14} activity of CO_2 in surface air of New Zealand as well as of wood and ocean carbonates. They found an average increase from 1954 to 1957 of about 2·1 per cent per year. A slight indication for an increase before 1954 was present in some results obtained in the Washington Radiocarbon Laboratory of the U.S. Geological Survey[3] from tree ring measurements. Similar results on different materials have been found by DE VRIES in Holland[4] and WILLIAMS in Houston[5]. The combined results show that the artificially-produced C^{14} had by 1957 increased the C^{14} content of atmospheric CO_2 by about ten per cent and hence greatly overcompensated for the effect of the combustion of fossil fuels that since the end of nineteenth century has led to a steady decrease in the specific C^{14} activity.

It seems remarkable that the first accurate measurements available were made on material from the Southern Hemisphere. More recently MÜNNICH and VOGEL[6] reported a large number of precise measurements on wood and seeds from Central Europe and South Africa. Because of the lack of precise work on material from North America the authors have investigated a tree from the coastal area of California. An attempt was made to obtain a sample from an area as free as possible from contamination by carbon dioxide from industrial sources. Dr. C. D. KEELING has been working for several years on the C^{13} concentration in atmospheric CO_2 in forests, and this experience assisted him in selecting a location which would have negligible admixture of carbon dioxide from artificial surces or from oxidation of forest soil.

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[1] LIBBY, W. F.: Science **123**, 657 (1956). — Proc. Nat. Acad. Sci. U.S.A. **42**, 365 (1956).

[2] RAFTER, R. A., and G. T. FERGUSSON: Science **126**, 557 (1957).

[3] SUESS, H. E.: Science **122**, 415 (1955).

[4] VRIES, H. L. DE: Science (in press).

[5] Private communications.

[6] MÜNNICH, K. O., and J. C. VOGEL: Naturwiss. (in press).

The tree supplied by Dr. KEELING was a Ponderosa Pine from the Los Padres National Forest, approximately one mile south of Cone Peak, elevation 4,000 feet, longitude 121°30′, latitude 36°07′. The location is about half way between San Francisco and Los Angeles and winds from the directions of these large cities are extremely rare in the area. The tree was growing on a ridge in a group of about five trees where the prevailing wind is from the ocean. Unfortunately it was discovered after the tree was cut that it was only some twenty years old and did not date from the 19th century. Although in general 19th century wood is taken as a standard, we can assume from other measurements that the decrease in the C^{14} activity since the 19th century due to artificial fuel combustion was about two per cent in that area around 1950[3]. The reference level for the reported increase can therefore be assumed to be about two per cent below the C^{14} activity of 19th century wood.

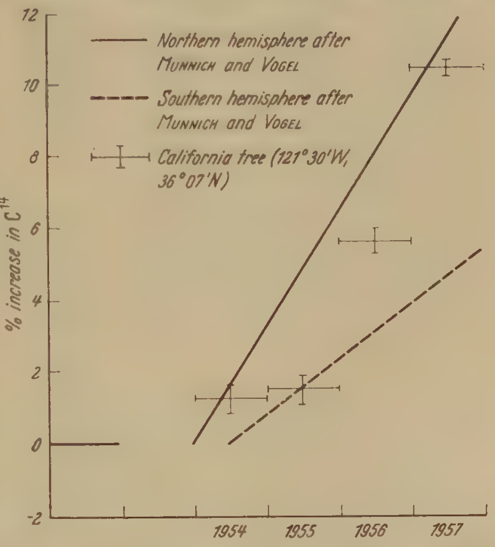

Fig. 1. Percent increase in the C^{14} concentration of terrestrial plant material since 1953

In order to avoid effects from diffusion of organic material within the tree the lignite was separated from the rest of the components of the wood. This was done by chopping the wood into shavings and treating with 6 N hydrochloric acid. After soaking at an elevated temperature for three days the wood disintegrated into smaller fragments which were filtered and boiled with water until acid free. This procedure should remove gums and most of the cellulose, so that only lignite remains. The procedure presumably led to some isotope fractionation, as was shown by C^{13} measurements. These measurements were carried out at the California Institute of Technology on CO_2 obtained by combustion of the acetylene used as the counting gas. Samples LJ-39 and LJ-40 were duplicate samples on wood from the inner rings of the tree. It is gratifying that the appreciable difference in the C^{14} activity of these two samples disappeared after correction for the difference in C^{13} concentration. The last column in Table 1 gives the observed increase in C^{14} in percent, normalized to the same C^{13} concentration[3]. The measurements agree within limits of error with the estimate of Münnich and Vogel. However, there seems to be some indication that the assumption of an increase linear with time is not a good approximation and that the increase from 1956 to 1957 was considerably larger than that from 1954 to 1955. No further conclusions can be drawn until more measurements have been carried out.

Table 1. *C^{14} Concentrations in Ponderosa Pine Tree Collected February 24, 1958*

Sample	Ring	Sample cpm	δC^{13} $\pm 0{\cdot}02$ (%)	δC^{14} (%)	$\left(\frac{1+\delta C^{14}}{1+2\delta C^{13}} - 1\right) \times 100$
LJ 41	1957	10·489	$+0{\cdot}065$	10·632	$+10{\cdot}49 \pm 0{\cdot}2$
LJ 47	1956	10·008	$-0{\cdot}055$	5·558	$+5{\cdot}67 \pm 0{\cdot}4$
LJ 46	1955	9·583	$-0{\cdot}198$	1·076	$+1{\cdot}48 \pm 0{\cdot}4$
LJ 45	1954	9·584	$-0{\cdot}083$	1·086	$+1{\cdot}25 \pm 0{\cdot}4$
LJ 39	1940—1945	9·178	$-1{\cdot}727$	$-3{\cdot}301$	$+0{\cdot}15 \pm 0{\cdot}3$
LJ 40	1940—1945	9·399	$-0{\cdot}361$	$-0{\cdot}872$	$-0{\cdot}15 \pm 0{\cdot}3$
Sandard from LJ 39 & 40		9·481			$\equiv 0$

This paper represents results of research carried out by the University of California under contract with the U.S. Atomic Energy Commission.

We appreciate the help of Ranger Campbell of the U.S. Forestry Service at King City in securing the investigated tree sample. Thanks are due to Dr. S. Epstein and Mrs. Irene Vidzuinas for the mass spectroscopic C^{13} determinations. We also wish to thank Drs. Münnich and Vogel for sending us their manuscript prior to its publication.

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DISTRIBUTION AND ECOLOGY OF FORAMINIFERA FROM EAST MISSISSIPPI DELTA MARGIN

BY

ROBERT R. LANKFORD

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VOL. 43, NO. 9 (SEPTEMBER, 1959), PP. 2068-2099, 11 FIGS., 3 PLS

DISTRIBUTION AND ECOLOGY OF FORAMINIFERA FROM EAST MISSISSIPPI DELTA MARGIN[1]

ROBERT R. LANKFORD[2]
La Jolla, California

ABSTRACT

Equal volume surface sediment samples from the eastern delta margin were studied for Foraminifera. Six faunal assemblages, based on living specimens are defined: (1) marsh, (2) interdistributary bay, (3) fluvial marine, (4) deltaic marine, (5) sound, and (6) open shelf. Bottom-water masses, characterized by limits of variability of the chemical and physical properties, coincide with the faunal distribution. No single property of the bottom water appears to be the controlling ecological factor. There does not seem to be any causal relation between faunas and sediment characteristics; both appear to result from other processes active in a deltaic environment. Maximum living populations are associated with the high sedimentation rates of the prograding delta front. The smallest standing crops occur where sedimentation rates are low. The total number of Foraminifera per sample ranges from 150 to 34,000 specimens and the maximum population zone is related to the area of highest foraminiferal productivity. Living and total counts are qualitatively similar except in areas where mud lumps containing relatively deep-water species are being eroded into shallow interdistributary bay deposits. Ratios of the living and total populations generally reflect effects of sedimentation.

Introduction

GENERAL STATEMENT

The purposes of this study are to investigate the distribution of foraminiferal assemblages in a part of the Mississippi Delta, particularly in the actively growing birdfoot delta, and to examine some of the environmental variables which may influence the faunal distribution. These analyses and interpretations should be of considerable value in recognizing various types of ancient delta deposits.

The present study supplements the work of Phleger in the eastern Mississippi Delta (1955), and in Mississippi Sound (1954). Other recent work on modern Foraminifera in the region includes the study of brackish-water pond and marsh species by Warren (1957) and the report by Treadwell (1955) on the fauna of Breton Sound and Chandeleur Sound and the adjacent marshes. Other studies of the distribution of modern Foraminifera in the northern Gulf of Mexico have been reported by Andersen (1951), Bandy (1954, 1956), Kornfeld (1931). Lowman (1949), Ludwick and Walton (1957), Parker (1954), Phleger (1951, 1956), and Phleger and Parker (1951).

METHOD OF STUDY

The area studied is in the eastern Mississippi Delta from approximately 29°08′–29°30′ N. Lat., and 88°45′–89°31′ W. Long. The sampling program was

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[1] Manuscript received, December 12, 1958. Contribution from the Scripps Institution of Oceanography, New Series; Marine Foraminifera Laboratory, Contribution No. 32. This investigation was supported by a grant from the American Petroleum Institute, Project 51.

[2] University of California, Scripps Institution of Oceanography. Boat facilities for the field work were provided by the Louisiana Wild Life and Fisheries Commission. The work was done under the supervision of Fred B Phleger. Many helpful suggestions were given by John S. Bradshaw, Jean P. Hosmer, Frances L. Parker, and Francis P. Shepard. Drafting was done by James R. Moriarty.

Contributions from the Scripps Institution of Oceanography, New Series, 1100

(552)

planned to include as many geographic units as were accessible during each of the field seasons. The stations (Fig. 1) were located by horizontal sextant angles and dead reckoning between known points.

Short cores of relatively undisturbed sediment were collected at 92 stations during November, 1955, February, 1956, and November, 1956, with a small gravity corer described by Phleger (1951). The top cm., approximately 10 ml. of wet sediment, was preserved in formalin and buffered and neutralized with hexamethylenamine and sodium carbonate. In three samples which contained an abundance of finely divided woody material the calcium carbonate was dissolved and only the protoplasm molds of Foraminifera remained.

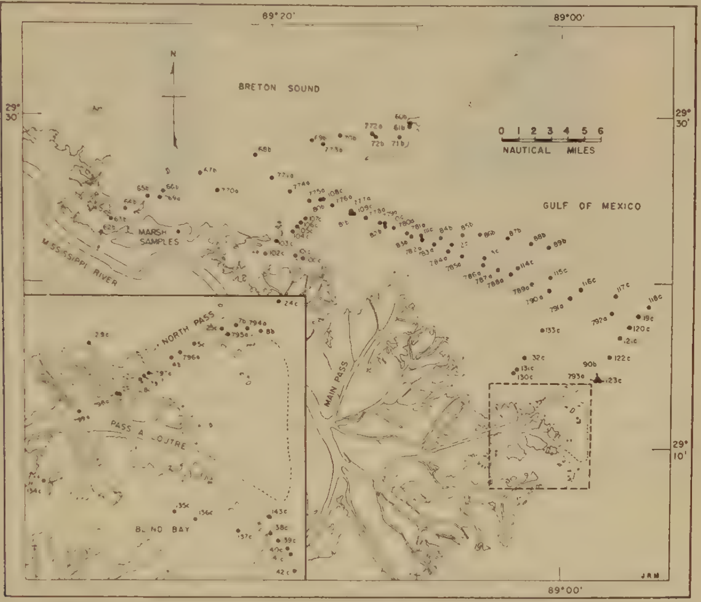

89°20'
89°00'
29° 30'
29° 30'
29° 10'
N
BRETON SOUND
0 1 2 3 4 5 6
NAUTICAL MILES
GULF OF MEXICO
MARSH SAMPLES
MISSISSIPPI RIVER
NORTH PASS
PASS A LOUTRE
MAIN PASS
BLIND BAY
JAM
89°00'

FIG. 1.—Locations of Stations. Letter suffix indicates season of collection: A = November, 1955; B = February, 1956; C = November, 1956.

Salinity and temperature determinations were made of bottom and surface water. Water samples were collected with a free-flushing plastic bottle which is automatically closed by a tripping device when the sampler hits the bottom (Fig. 2).

Living specimens were identified by use of rose Bengal stain (Walton, 1952). Samples were washed over a sieve having an average opening of 0.062 mm. and the wet residue was examined for living Foraminifera. In addition, the maximum linear dimension of living individuals was measured with an ocular micrometer.

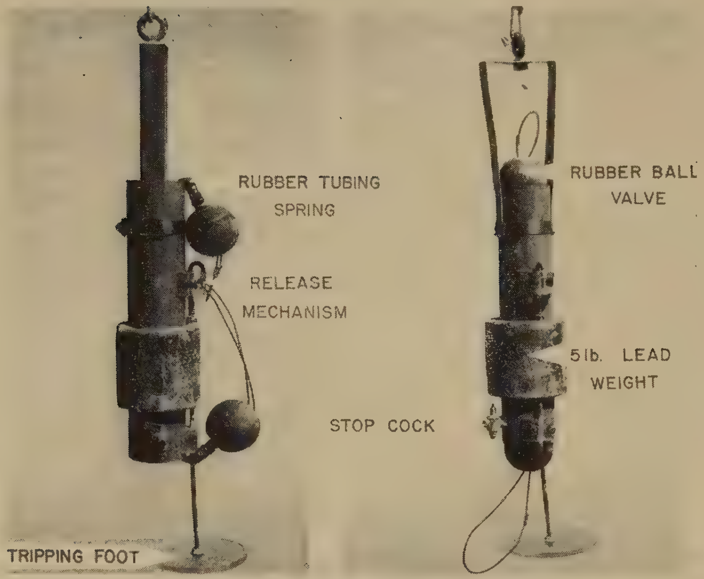


Fig. 2.—Bottom-water sampler shown in opened (left) and closed (right) positions.

If living individuals of a species were abundant in a sample, the measurements of only the first 55 encountered specimens of a species were recorded. Previous work with length measurements (Phleger and Lankford, 1956) indicates that this technique gives sufficiently reliable length data. Total populations were counted after drying.

DESCRIPTION OF AREA

GENERAL STATEMENT

The modern birdfoot delta of the Mississippi River is principally a sedimentary feature and includes the many distributaries bordered by natural levees and separated by marsh and very shallow bays. The northern distributaries are rapidly prograding into the relatively shallow inlet between Breton Island and the mainland. The southern distributaries are building forward into the Gulf of Mexico's relatively deep water at a slower rate.

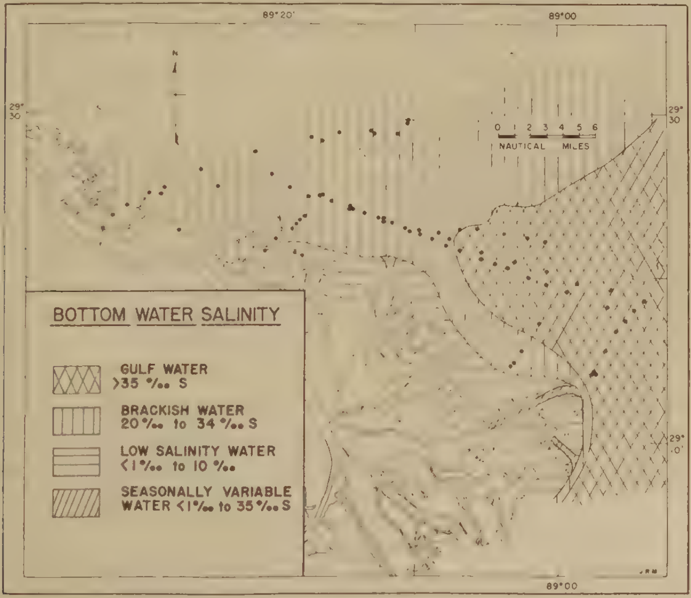
Breton Sound is a large shallow bay with an average depth of approximately 10 feet and covers much of the submerged part of the abandoned St. Bernard subdelta. The seaward part of this ancient subdelta has been subjected to continuing wave attack and the winnowed sands resulting from these processes now form Breton Island and the chain of other barrier islands extending northeast. The barrier islands are interrupted by relatively wide inlets between the sound and Gulf of Mexico.

(554)

WATER CHARACTERISTICS

The physical oceanography has been reported by Scruton (1956), based on his own observations and additional data from other sources. The temperature and salinity data are from bottom-water samples. Surface values are not discussed because they are highly variable in the vicinity of the Mississippi Delta and probably have only limited effect on benthonic organisms.

Figure 3 shows the generalized distribution of bottom-water salinity compiled from measurements made during this study and from those reported by Geyer (1955), Scruton (1956), and Treadwell (1955). Values obtained on the open continental shelf and in the deeper water adjacent to the delta are those of normal Gulf water and show little seasonal change. Brackish water with values ranging from 20°/₀₀ to 34°/₀₀ S occurs in Breton Sound, in the small shallow bays north of the active distributaries, and in a narrow band peripheral to the birdfoot delta. This intermediate salinity water varies somewhat with seasonal river discharge and climatic conditions. The salinity in the very shallow interdistributary bays rarely exceeds 10°/₀₀, even during periods of low river runoff. During flood stages, river water flushes the bays and the salinity may drop to less than 1°/₀₀. The bottom-water salinity of the distributary channels is usually less than 1°/₀₀ when the Mississippi River is at its flood stage. When river discharge decreases, a wedge of saline Gulf water of greater density invades along


89°20'
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N
0 1 2 3 4 5 6
NAUTICAL MILES
29° 0'
89°00
BOTTOM WATER SALINITY
GULF WATER >35 °/₀₀ S
BRACKISH WATER 20 °/₀₀ to 34 °/₀₀ S
LOW SALINITY WATER <1 °/₀₀ to 10 °/₀₀
SEASONALLY VARIABLE WATER <1 °/₀₀ to 35 °/₀₀ S

FIG. 3.—Generalized distribution of bottom-water salinity.

the channels and moves upstream under the outflowing low-density river water. When the salt wedge is present, salinity values as high as 32°/oo have been measured in North Pass and Pass a Loutre. A highly variable salinity regime is thus characteristic of this environment.

The temperature of the bottom water has a pattern of variation similar to that of salinity. In general, the deeper water on the shelf and next to the delta has a relatively small temperature range. The shoaler waters in the sound are influenced by the temperature of the river as well as by variable weather. Vertical mixing by wind and waves may occur in very short periods so that short term temperature changes at the surface are soon communicated to the bottom water. The most extreme temperature changes are found in the marsh and interdistributary bays where the shallow water is readily influenced by the diurnal, climatic, and seasonal changes in air temperature. Water temperatures may be several degrees warmer than air temperatures. Bottom water in the distributary passes shows a long-term seasonal range in temperature but apparently short-term variations are not as pronounced as they are in the other environments of the delta's topset beds.

The pH measurements of the water given by Scruton (1956, pp. 2930–31) appear to increase only slightly with salinity. The range of averages is from pH 7.85 at 1°/oo S to pH 8.05 at 35°/oo S; a few low values of pH 6.7–7.0 were recorded in low-salinity water near the delta. Scruton believes that pH differences produced by other factors such as biological activity exceed differences related to salinity. Treadwell (1955) found no trend in his pH values along a traverse extending across the marshland and into inner Chandeleur Sound. Butler (1952) on the other hand found that in Mississippi Sound, the pH usually increased with salinity values.

Distribution of water units having similar properties appears to be partly controlled by the physiography of the area. The distribution of these water types, with particular reference to the bottom water, approximately coincides with the distribution of foraminiferal assemblages. The principal chemical and physical variables in the waters overlying the foraminiferal environments are summarized in the following paragraphs. All notations refer to bottom water except where the measurements were made in water less than about 2 feet deep.

CHARACTERISTICS OF BOTTOM WATER

Marsh.—Water depths usually less than one foot; salinity generally less than 20°/oo (infrequent high values due to evaporation or high storm tides); temperatures are atmospheric but may be higher than air temperatures in summer months.

Interdistributary bay.—Water depths from a few inches to 3–6 feet; salinity consistently low, from less than 1°/oo to 10°/oo; temperatures' known range is from 0°C. to 38°C.; turbidity and turbulence may result from wave action or currents in and near the river-connecting crevasses.

Fluvial marine.—Water depths less than 5 to about 30 feet; salinity values vary inversely as the height of the river, from less than 1°/oo during high stages to 32°/oo during low stages when the "salt wedge" invades along the deeper parts of the channel; river temperatures, from about 8°C. to 29°C., generally lag behind the regional air temperatures; turbidity and turbulence relatively high along the bottom except when and where the "salt wedge" is operative.

Deltaic marine.—Upper depth limit about 30 feet, lower depth limit unknown; salinity nearly normal for the Gulf, 34°/oo to 36°/oo; bottom temperatures reflect the Gulf control with the maximum range at 100 feet about 19°C. to 30°C., the seasonal average from 21°C. to 26°C.; turbulence, a function of water depth, wave height, and currents, generally decreases with depth; turbidity values high along the bottom but decrease with distance away from the delta.

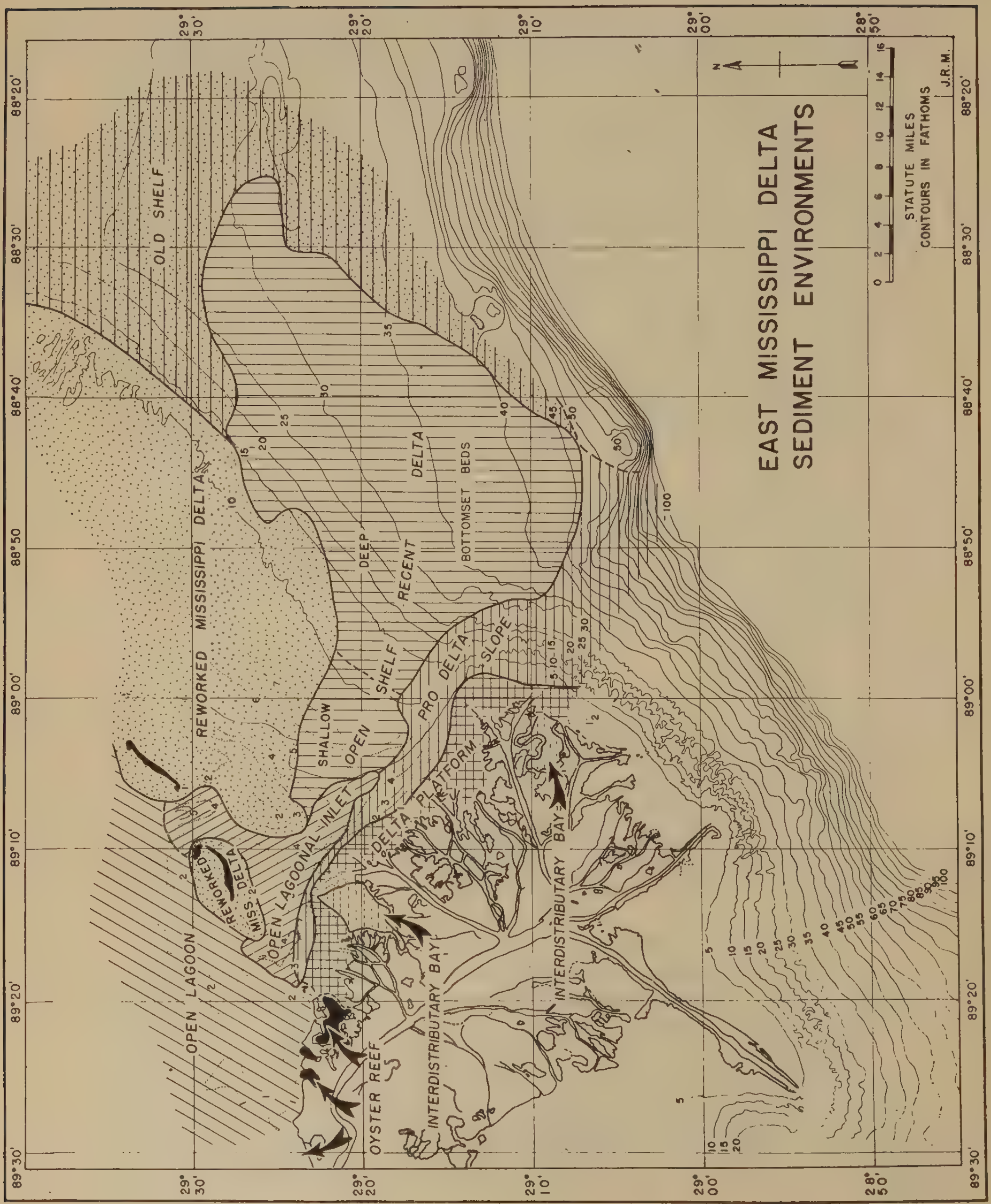
Sound.—Water depths from less than 3 to about 30 feet; over-all salinity values throughout the length of the environment 18°/oo to 36°/oo, at any one place the variation is within a 10°/oo range; temperatures from about 15°C. to 30°C. with higher and lower extremes, with the atmosphere and solar radiation as primary influences; turbulence from small waves and currents; relatively turbid water.

Open shelf.—Water depths from open Gulf beaches to the shelf break (approximately 65 fathoms); salinity values show a very small range around 36°/oo; Gulf temperatures seasonal, ranging from 17°C. to 31°C. at the surface and from 16°C. to 22°C. on the bottom at the shelf edge; turbulence decreases with depth; turbidity decreases to very small values away from land.

SEDIMENTS

Distribution.—Recent sediments in the eastern delta area have been investigated by Inman and Chamberlain (1955), Scruton (1955), Treadwell (1955), and Shepard (1956). Three broad genetic categories of sediments may be differentiated: (1) the river-borne sediments now being deposited to constitute the various aspects of the delta; (2) sediments reworked from the now-abandoned and partly submerged St. Bernard subdelta, and (3) the shelf "sands" which apparently were not derived from the Mississippi drainage basin. The distribution of these three groups and the environments of deposition are shown in Figure 4. These general sediment categories have been subdivided according to certain physical and compositional parameters. Figure 5-a shows the areal distribution of eight sediment types and subtypes which have been recognized by Inman and Chamberlain (1955) in the area; the relation of these types to median diameter, phi deviation, and phi skewness is given in Figure 5-b.

Hydrogen ion concentration.—The hydrogen ion concentration of the surface sediment has been measured at many stations by members of API Project 51 using Beckman pH meters. The values were obtained during 1951 and 1952 using two techniques for measurements. The first consisted of taking a core and immediately inserting the electrodes into the upper layer of the sediment. The


EAST MISSISSIPPI DELTA
SEDIMENT ENVIRONMENTS
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N
OLD SHELF
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REWORKED MISS. DELTA
OPEN LAGOON
OPEN LAGOONAL INLET
SHALLOW OPEN SHELF
DEEP RECENT DELTA
DELTA BOTTOMSET BEDS
PRO DELTA SLOPE
DELTA PLATFORM
INTERDISTRIBUTARY BAY
OYSTER REEF
88°20'
88°30'
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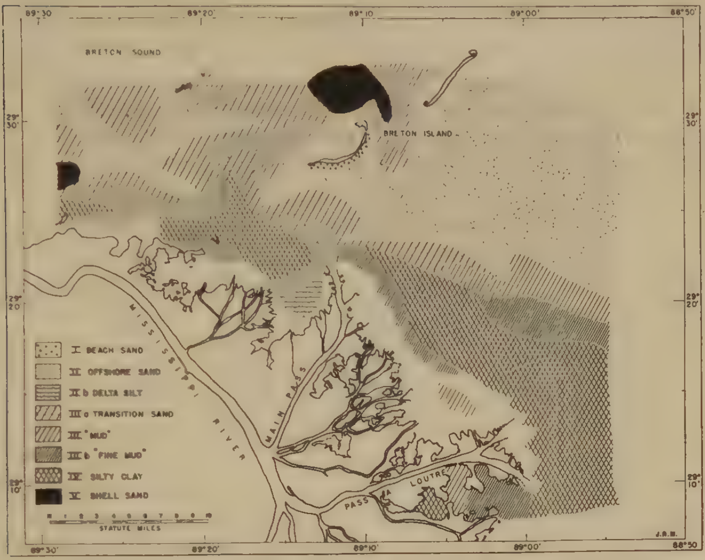
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29° 20'
29° 10'
BRETON SOUND
BRETON ISLAND
MISSISSIPPI RIVER
MAIN PASS
LOUTRE PASS
I BEACH SAND
II OFFSHORE SAND
II b DELTA SILT
III a TRANSITION SAND
III "MUD"
III b "FINE MUD"
IV SILTY CLAY
V SHELL SAND
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES
J.R.B.

FIG. 5a.—Areal distribution of sediment types. Types are defined in Figure 5b. After D. L. Inman and T. K. Chamberlain.

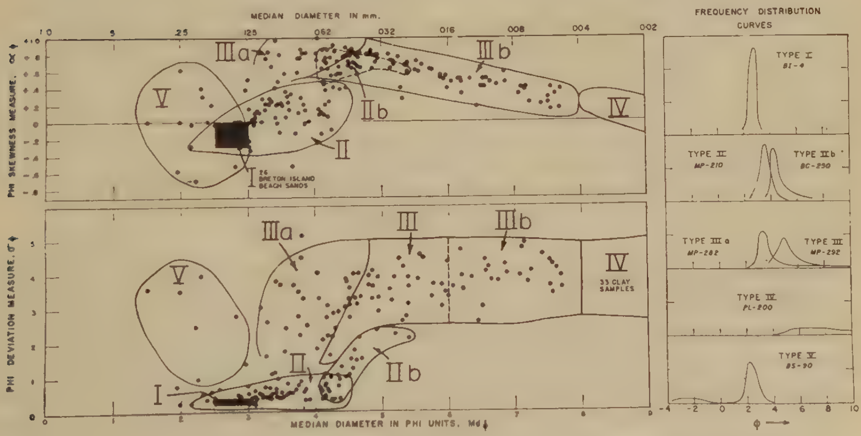
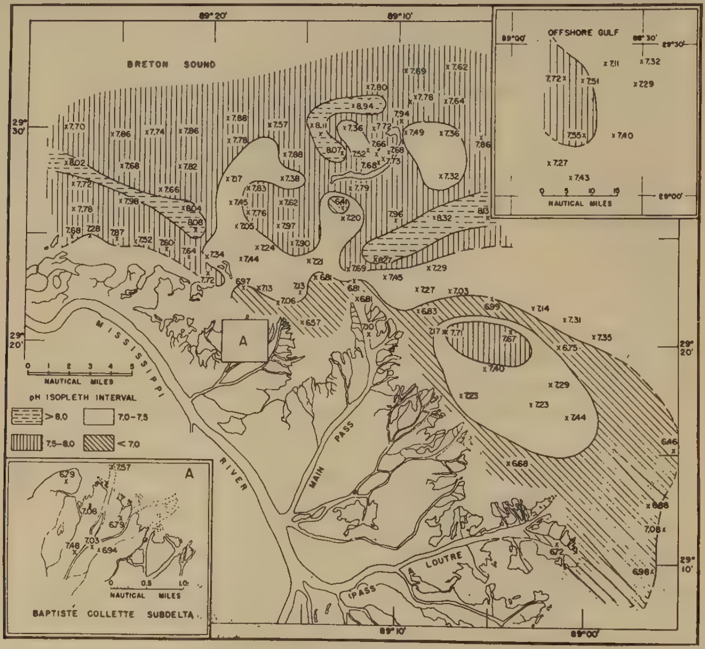


FIG. 5b.—Size distribution diagram of sediments with frequency distribution curves of typical sediments. After D. L. Inman and T. K. Chamberlain.

second technique used 50-foot experimental leads which allowed the electrodes to be lowered to the bottom for *in situ* measurements. A correction factor was calculated to take into consideration the different electrical properties of the longer electrode leads. The pH values obtained are in Figure 6.

Both techniques are relatively inaccurate and the isopleth trends in the offshore area become more important than the actual reported values. In the very shallow water and marsh area shown in Insert A of Figure 6, the pH values are generally low and show no noticeable distribution pattern. There are two possible reasons for this. Vegetation is limited to very shallow water and to the marsh areas where vegetation is generally abundant but patchy. Areal variations in the amount of plant material living and decaying in the surface sediments would produce an irregular pH distribution pattern. A second possibility for erratic values in shallow areas is discussed by Stewart (1956). He found that in lagoon shallows having heavy plant growth, large diurnal pH changes ordinarily mask any geographic differences or patterns which might occur. He attributes this to the diurnal changes in photosynthetic rates which directly affect the hydrogen ion concentration.


89° 20'
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BRETON SOUND
OFFSHORE GULF
89° 00'
88° 30'
0 5 10 15
NAUTICAL MILES
29° 30'
29° 20'
29° 10'
MISSISSIPPI RIVER
MAIN PASS
LOUTRE PASS
A
0 1 2 3 4 5
NAUTICAL MILES
pH ISOPLETH INTERVAL
>8.0
7.0–7.5
7.5–8.0
< 7.0
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0
NAUTICAL MILES

FIG. 6.—Distribution of pH in surface sediments.

ZoBell (1946) reports that each sediment type seems to have its own characteristic Eh and pH. Comparison of the pH trends with distribution of sediment characteristics (Figs. 5-a and 6) shows many similarities. The coarser-grained and better sorted sediments have high pH values which are approximately equal to those of the overlying water. The more poorly sorted and finer-grained sediments adjacent to the actively growing delta are characterized by lower pH measurements.

The physical parameters of the sediment are not believed to have any direct relation to hydrogen ion concentration except in their control of interchange of interstitial water and the overlying water. The primary factor controlling sediment pH may be the abundance of organic material. The Mississippi River discharges large quantities of organic detritus particularly during high-water stages which are incorporated in the sediment. Unpublished analyses show a relation between increasing clay content and increasing "total organic carbon" and nitrogen content; pH varies inversely as the carbon and nitrogen content. The environmental processes which produce relatively coarse and well sorted sediments prevent accumulation of detrital organic material.

FORAMINIFERAL FAUNAS

Most of the samples were collected from interdistributary bay, fluvial marine, sound, and deltaic marine foraminiferal environments. The marsh and open shelf were only sparsely sampled. Previous work in these two environments has been relatively extensive and their faunal characteristics are well known. Faunal analyses and population counts are given in Tables II, III, and IV. Figures of the 50 most common species are in Plates I, II, and III. Figured specimens are deposited in the U. S. National Museum; additional reference materials are in the collections of the Marine Foraminifera Laboratory.

Each fauna defined in the following paragraphs is characterized by different genera and species and (or) differences in frequencies of genera and species which occur in more than one fauna.

The relative abundances of the common species are shown in Figure 7. Distribution of faunal associations is given in Figure 8. The sharpest breaks between faunas are found in shallow water; for example, the marsh and interdistributary bay or marsh and sound assemblages may live within a few feet of each other and show relatively little mixing. The boundaries between deltaic marine, shelf, and sound faunas, however, may be broadly gradational and the assignment of mixed associations of Foraminifera to a specific assemblage becomes more difficult.

Marsh.—This is the most distinctive of all known foraminiferal faunas. It is characterized by poorly cemented arenaceous species which have world-wide distribution. Calcareous forms usually are rare. Marshes have abundant decaying vegetation and the resulting acid conditions may dissolve dead tests of calcareous species. Frances L. Parker (personal communication) found living calcareous species in a Cape Cod marsh but only infrequently were the dead tests preserved in these organic sediments. Arenaceous species which are restricted to the marsh in the present area include the following.

Ammoastuta inepta Cushman and McCulloch
Arenoparrella mexicana (Kornfeld)
Haplophragmoides manilaensis Andersen
H. wilberti Andersen
Sulcophax palustris Warren
Textularia palustris Warren
Trochammina inflata (Montagu)
T. macrescens Brady

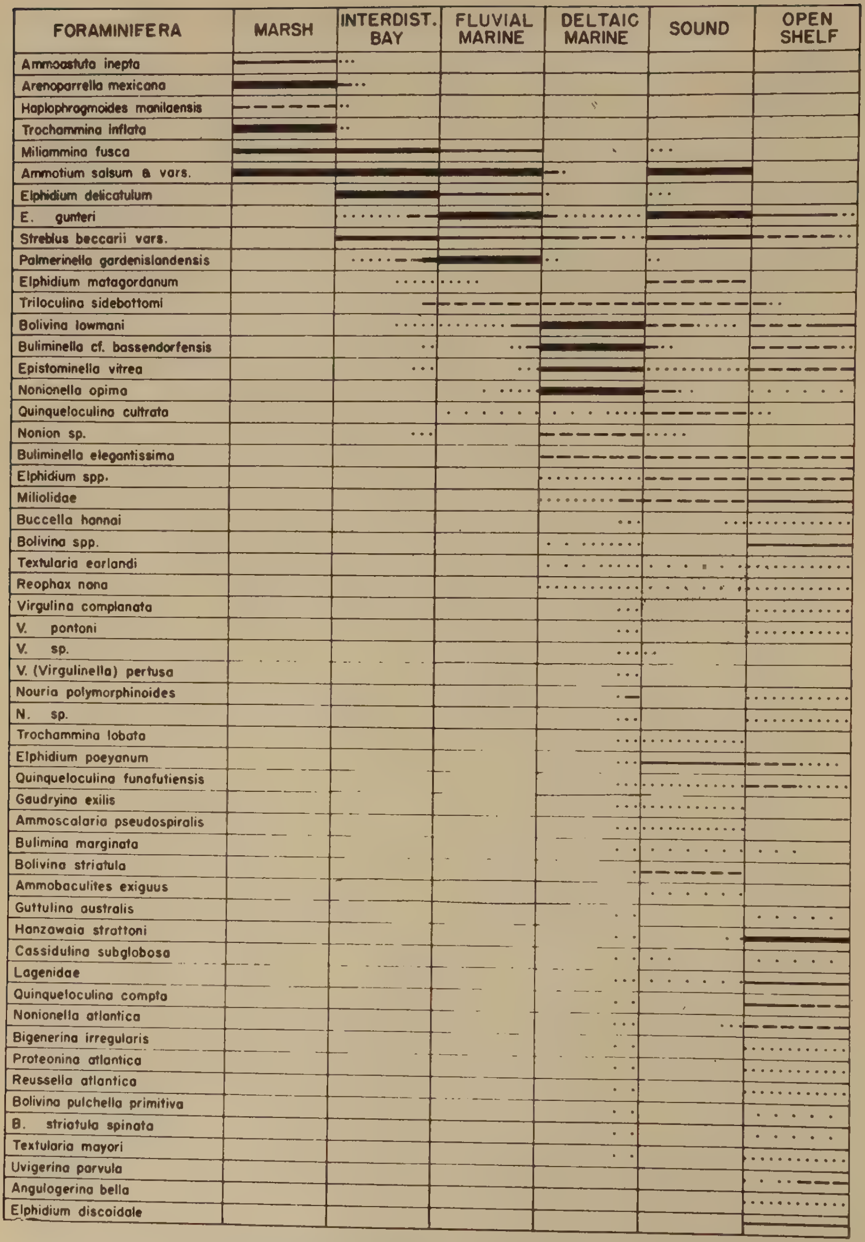


FIG. 7.—Generalized distribution of the most abundant living Foraminifera species. Weight of line indicates relative abundance of species in each faunal association.

In addition to these restricted species, *Ammotium salsum* (Cushman and Bronnimann) and variants and *Miliammina fusca* (Brady) also occur in abundance.

The outer boundary of this assemblage appears to be relatively well defined although marsh species are found in low frequencies in shallow bays adjacent to marshes. Their presence in these bays probably indicates lateral transport into a reproductively sterile habitat.

Interdistributary bay.—This fauna is characterized by abundance of *Elphidium delicatulum* Bermudez. The following species occur in significant frequencies.

Ammotium salsum (Cushman and Bronnimann) and vars.
Elphidium gunteri Cole
Miliammina fusca (Brady)
Streblus beccarii (Linné) vars.

Where a crevasse or bayou connects the river to the interdistributary bay, *Palmerinella gardenislandensis* (Akers) is found in abundance and reflects the influence of river water.

The faunal association extends from the marsh edge to, and including, the submerged natural levees bordering the river and seaward to a water depth of about 6 feet. Beyond this depth there is a transition zone to the adjacent environment.

Fluvial marine.—This fauna is similar in species content to the interdistribu-

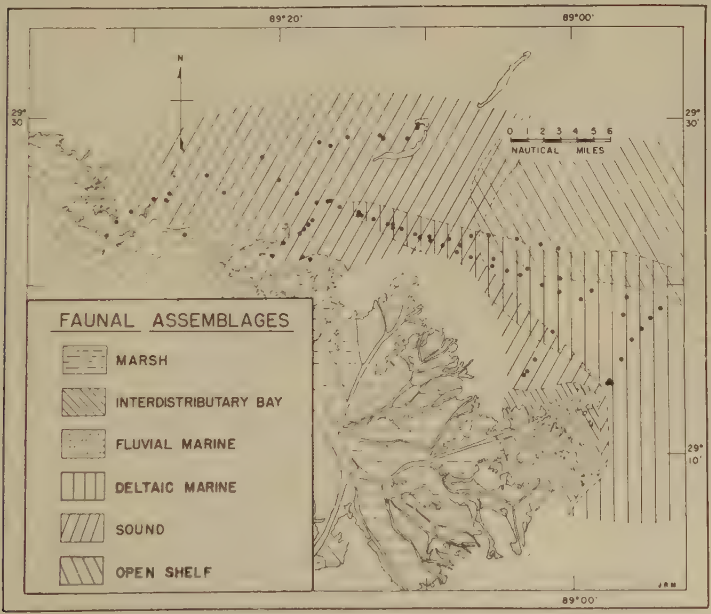
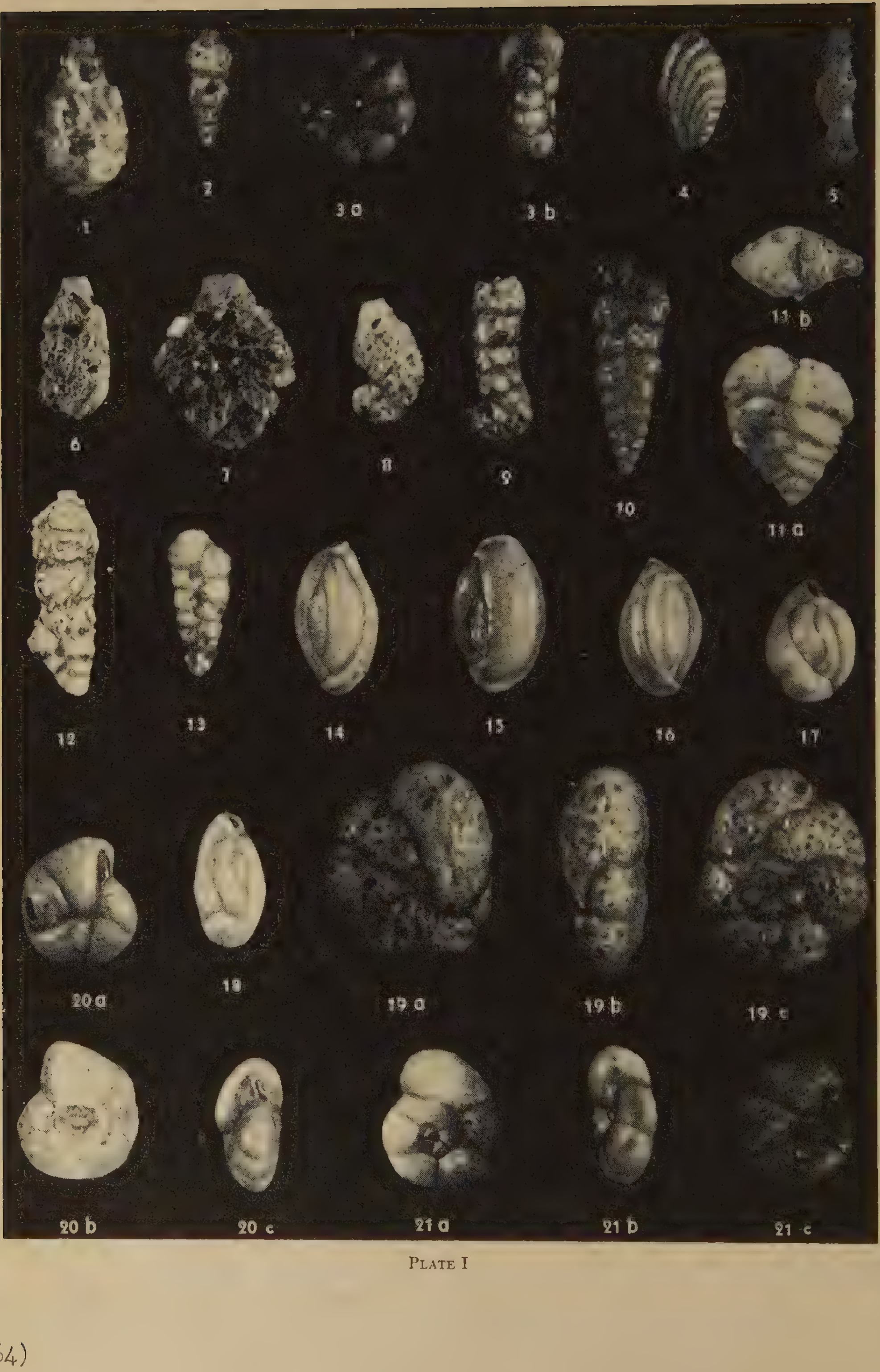

89°20'
89°00'
N
29° 30
29° 30'
0 1 2 3 4 5 6
NAUTICAL MILES
FAUNAL ASSEMBLAGES
MARSH
INTERDISTRIBUTARY BAY
FLUVIAL MARINE
DELTAIC MARINE
SOUND
OPEN SHELF
29° 10'
J.R.M.
89°00'

FIG. 8.—Areal distribution of faunal assemblages. Overlap of patterns indicates gradational boundaries between assemblages.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19 a
19 b
19 c
20 a
20 b
20 c
21 a
21 b
21 c

Plate I

tary bay and sound assemblages but differs in relative abundances of the species. *Palmerinella gardenislandensis* (Akers) in abundance is the typical species. At the mouths of passes the fluvial marine fauna contains specimens of *Bolivina lowmani* Phleger and Parker, *Nonionella opima* Cushman, *Epistominella vitrea* Parker, *Buliminella* cf. *B. bassendorfensis* Cushman and Parker and other rare species more typical of the sound and deltaic marine environments.

The upstream limit of the fluvial marine assemblage is not known but it probably is controlled by the upper limits of the salt-water wedge. The seaward extent approximately coincides with the river-mouth bar, beyond which the sound and deltaic marine faunas replace the fluvial marine association.

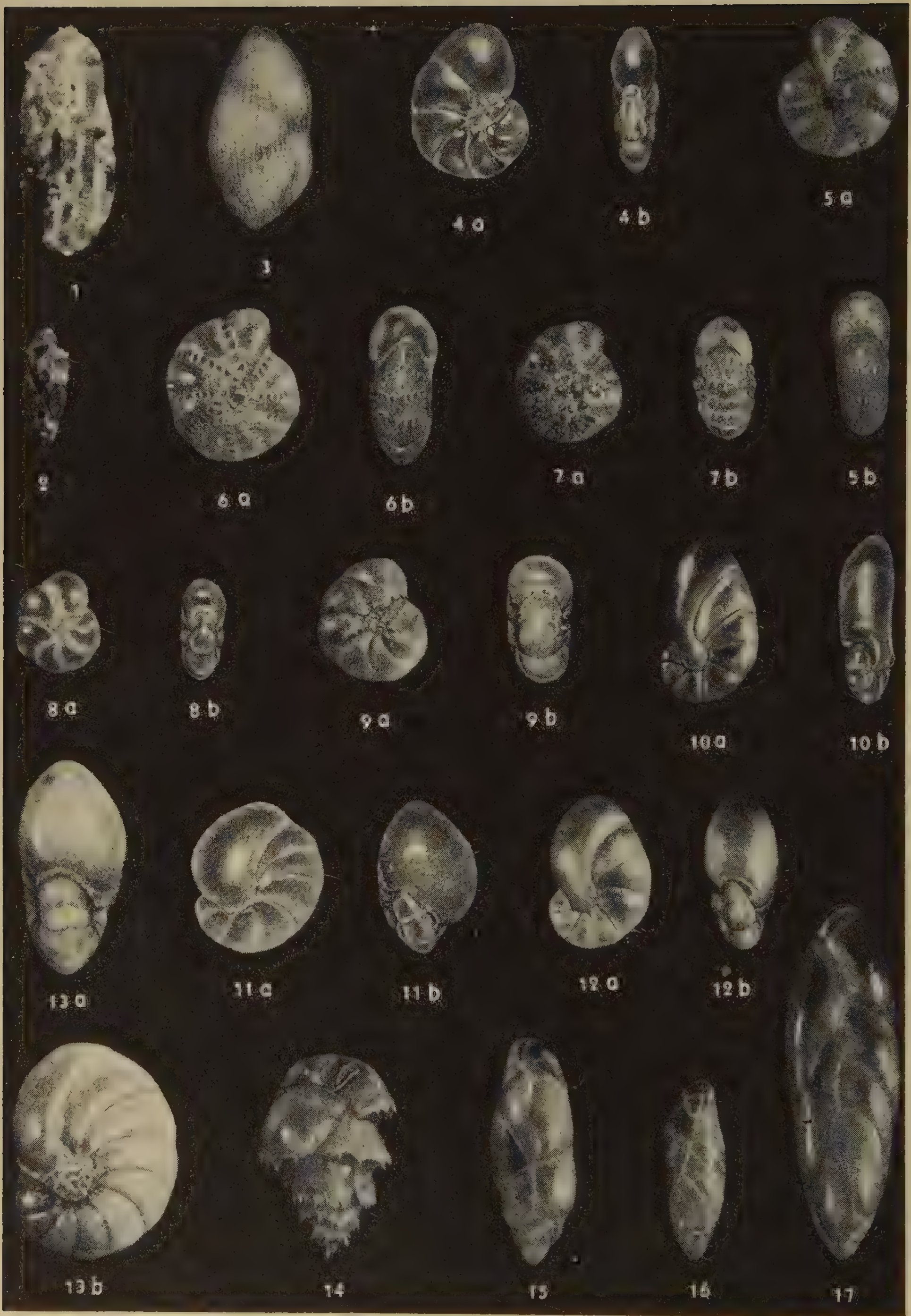
Deltaic marine.—The deltaic marine fauna occurs on the actively prograding delta where sedimentation rates are high and there is an essentially marine environment. The fauna is characterized by *Bolivina lowmani* Phleger and Parker, *Buliminella* cf. *B. bassendorfensis* Cushman and Parker, *Epistominella vitrea* Parker, and *Nonionella opima* Cushman which commonly constitute more than 90 per cent of the exceptionally large living population. Most of the species found in the open-shelf and sound assemblages also occur in the deltaic marine fauna but in very low frequencies.

Distribution of the deltaic marine association approximately coincides with the overlap of rapid sedimentation with normal Gulf water. Away from the delta in relatively deep water, sedimentation decreases and there is a broad zone of mixing between the deltaic marine and open-shelf assemblages. In shoaler water, adjacent to the delta and in the deeper bays, the deltaic marine species mix with those of the sound environment. The boundary between the two environments may be sharp or gradational, depending on the mixing gradient between the Gulf and river waters.

←

EXPLANATION OF PLATE I

1. *Lagenammina atlantica* (Cushman). ×105. Sta. 791.
2. *Reophax nana* Rhumbler. ×95. Sta. 114.
3. *Haplophragmoides manilaensis* Andersen. ×125. Sta. Marsh.
4. *Ammoastuta inepta* (Cushman and McCulloch). ×60. Sta. Marsh.
5–7. *Ammoscalaria pseudospiralis* (Williamson). ×35. Sta. 791.
8. *Ammotium salsum* (Cushman and Bronnimann). ×60. Sta. Marsh.
9. *Ammobaculites exiguus* Cushman and Bronnimann. ×95. Sta. 791.
10. *Textularia earlandi* Parker. ×115. Sta. 121.
11. *Textularia mayori* Cushman. ×55. Sta. 791.
12. *Bigenerina irregularis* Phleger and Parker. ×55. Sta. 791.
13. *Gaudryina exilis* Cushman and Bronnimann. ×95. Sta. 109.
14. *Quinqueloculina compta* Cushman. ×55. Sta. 791.
15. *Quinqueloculina cultrata* (Brady). ×55. Sta. 791.
16. *Quinqueloculina funafutiensis* (Chapman). ×55. Sta. 791.
17. *Triloculina sidebottomi* (Martinotti). ×95. Sta. 121.
18. *Miliammina fusca* (Brady). ×60. Sta. Marsh.
19. *Trochammina lobata* Cushman. ×85. Sta. 81.
20. *Arenoparrella mexicana* (Kornfeld). ×80. Sta. Marsh.
21. *Trochammina inflata* (Montagu). ×80. Sta. Marsh.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7 a
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5 b
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9 b
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10 b
13 a
11 a
11 b
12 a
12 b
13 b
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PLATE II

Sound.—The sound assemblage is similar to that found in many bays and sounds along the northern Gulf Coast. In the delta area it occurs most typically in Breton and Chandeleur sounds and adjacent embayments. The most common species include the following.

Ammoscalaria pseudospiralis (Williamson)
Ammotium salsum (Cushman and Bronnimann) and vars.
Elphidium gunteri Cole
E. matagordanum (Kornfeld)
E. poeyanum (d'Orbigny)
Miliolidae
Streblus beccarii (Linné) vars.
Triloculina sidebottomi (Martinotti)

Bolivina striatula Cushman seems to be restricted to the sound environment but occurs only in small numbers.

The sound fauna also is found at the south in a narrow band around the shallow parts of the actively growing delta front.

Open shelf.—Samples from the area beyond the delta's influence contain an open-shelf fauna typical of the northern Gulf of Mexico. The following species are characteristic of this environment.

Bigenerina irregularis Phleger and Parker
Bolivina spp.
Buccella hannai (Phleger and Parker)
Elphidium discoidale (d'Orbigny)
E. spp.
Eponides antillarum (d'Orbigny)
Guttulina australis (d'Orbigny)
Hanzawaia strattoni (Applin)
Nodosariidae
Nonionella atlantica Cushman
Nouria polymorphinoides Heron-Allen and Earland
N. sp.
Lagenammina atlantica (Cushman)
Quinqueloculina compta Cushman
Q. horrida Cushman
Q. lamarckiana d'Orbigny
Reussella atlantica Cushman
Textularia mayori Cushman
Uvigerina parvula Cushman
Virgulina complanata Egger
V. pontoni Cushman

The species composition is similars to that reported by others from the northern Gulf of Mexico. There is no indication that any species or group of species is dominant as in the deltaic marine assemblage.

FORAMINIFERA POPULATIONS

Living Foraminifera.—The numbers of living specimens per equal volume

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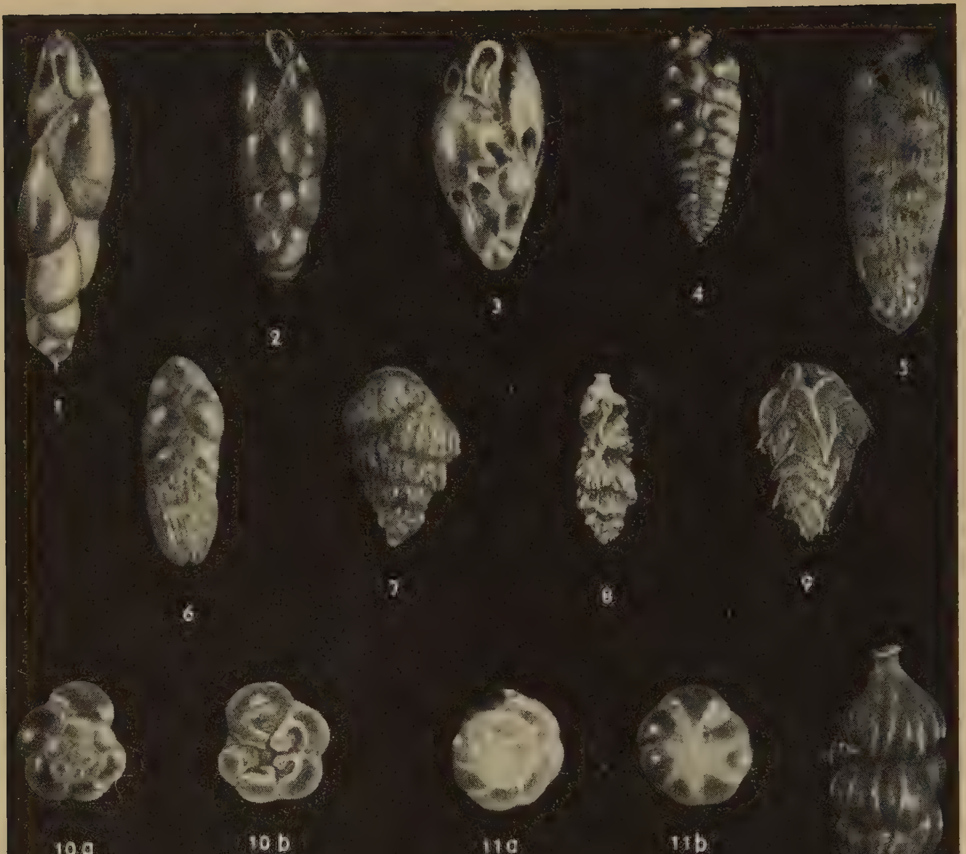
←«««

Explanation of Plate II

1. *Nouria polymorphinoides* Heron-Allen and Earland. ×60. Sta. 791.
2. *Nouria* sp. ×60. Sta. 791.
3. *Guttulina australis* (d'Orbigny). ×55. Sta. 791.
4. *Nonion* sp. ×95. Sta. 118.
5. *Elphidium poeyanum* (d'Orbigny). ×55. Sta. 109.
6. *Elphidium discoidale* (d'Orbigny). ×55. Sta. 791.
7. *Elphidium gunteri* Cole. ×75. Sta. 109.
8. *Elphidium matagordanum* (Kornfeld). ×75. Sta. 109.
9. *Elphidium delicatulum* Bermudez. ×80. Sta. 135.

10–12. *Nonionella opima* Cushman. Fig. 10, ×125. Sta. 121; Fig. 11, ×85. Sta. 791; Fig. 12, ×95. Sta. 121.

13. *Nonionella atlantica* Cushman. ×80. Sta. 791.
14. *Bulimina marginata* d'Orbigny. ×125. Sta. 791.
15. *Buliminella* cf. *B. bassendorfensis* Cushman and Parker, ×115. Sta. 121.
16. *Buliminella elegantissima* (d'Orbigny). ×115. Sta. 114.
17. *Virgulina pontoni* Cushman. ×125. Sta. 791.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10 a
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11 a
11 b
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13 a
13 b
14 a
14 b
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16 a
16 b
16 c
17 a
17 b
17 c

Plate III

sample are illustrated in Figure 9. The largest living populations yet found in the Gulf of Mexico occur in a broad band bordering the southeastern Mississippi Delta. Generally, the numbers of living specimens per sample are somewhat larger than those given by Phleger (1955, Fig. 8). The difference is probably due to laboratory procedure. Phleger used a 200-mesh sieve (0.074 mm.), whereas a 230-mesh (0.062 mm.) screen was used in this investigation. The size of specimens in the delta area usually is small. This is particularly true in the deltaic marine environment.

Standing crops in the deltaic marine environment range from 200 to 8,000 living specimens per sample. A zone of maximum population occurs on the bottomset beds off the major distributaries. The average in this area is approximately 2,500 live Foraminifera per 10 square centimeters of bottom area. The living population decreases rather abruptly away from the delta onto the open continental shelf. The decrease is more gradual up the prograding delta front. The living counts are highly variable in the marsh, interdistributary bay, and fluvial marine assemblages. Populations range from as few as four to as many as 700 Foraminifera per sample and show no pattern. The smallest average standing crops within the area studied occur in the open-shelf environment away from more active deltaic sedimentation and in most of Breton Sound. Standing crops in these areas usually are less than 100 and the average is approximately 60 living specimens per sample.

The median specimen size of the more abundant species normally is small in areas of large standing crops. Length data of *Bolvina lowmani* and *Nonionella opima* were analyzed because both species are relatively abundant. In addition, the inshore limits of their environmental distribution are well defined. Living specimens were measured to the nearest 0.025 mm. and the arithmetic mean length of each species was computed for samples having ten or more specimens of a species present. The sample means were averaged within environments and the results are in Table I.

←«««

EXPLANATION OF PLATE III

1. *Virgulina complanata* Egger. ×125. Sta. 118.
2. *Virgulina* sp. ×175. Sta. 118.
3. *Virgulina (Virgulinella) pertusa* Reuss. ×125. Sta. 118.
4. *Bolivina lowmani* Phleger and Parker. ×135. Sta. 791.
5. *Bolivina striatula spinata* Cushman. ×120. Sta. 791.
6. *Bolivina striatula* Cushman. ×125. Sta. 109.
7. *Bolivina pulchella primitiva* Cushman. ×130. Sta. 791.
8. *Angulogerina bella* Phleger and Parker. ×60. Sta. 791.
9. *Reussella atlantica* Cushman. ×65. Sta. 791.
10. *Streblus beccarii* (Linné) variant. ×55. Sta. 791.
11. *Buccella hannai* (Phleger and Parker). ×85. Sta. 791.
12. *Uvigerina parvula* Cushman. ×130. Sta. 791.
13. *Streblus beccarii* (Linné) variant. ×55. Sta. 791.
14. *Epistominella vitrea* Parker. ×80. Sta. 791.
15. *Cassidulina subglobosa* Brady. ×115. Sta. 791.
16. *Hanzawaia strattoni* (Applin). ×55. Sta. 791.
17. *Palmerinella gardenislandensis* (Akers). ×85. Sta. 136.

Table I. Comparative Mean Length Data

Faunal Environment	*Bolivina lowmani* *Mean Length (mm.)*	*Nonionella opima* *Mean Length (mm.)*
Sound	0.198	0.223
Deltaic marine	0.175	0.185
Fluvial marine	0.218	—
Open shelf	0.205	—
Average of all samples	0.193	0.198

The mean length of both species is smallest in the deltaic marine environment where *B. lowmani* and *N. opima* commonly total more than 50 per cent of the large living population. In the sound environment, *N. opima* occurs in lower frequencies and has a 20 per cent greater mean length than in the deltaic marine samples; this species does not occur in the other environments in sufficient quantities for analysis. *Bolvina lowmani* is relatively rare in the fluvial marine samples and is approximately 25 per cent longer here than in the deltaic marine environment. The mean length of this species is intermediate in the sound and open-shelf environments. It is assumed that large numbers of living Foraminifera result from optimum growth and reproductive conditions and a scarcity of specimens is evi-

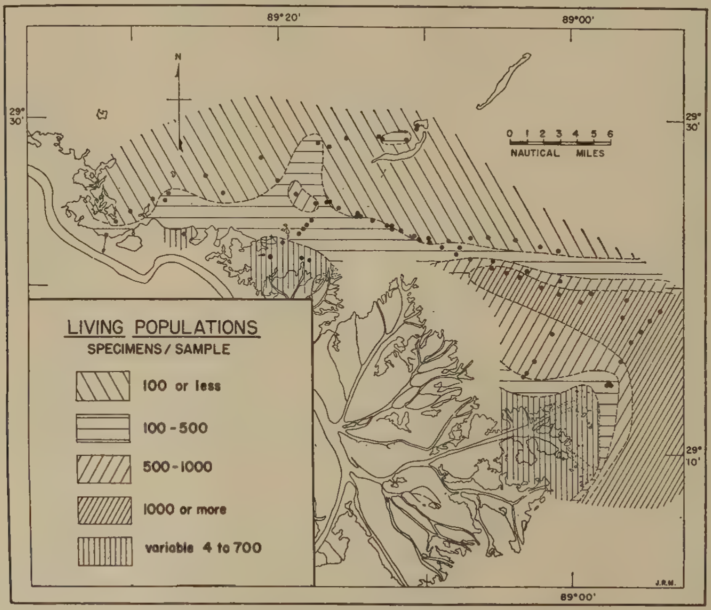
89°20'
89°00'
N
29° 30'
29° 30'
0 1 2 3 4 5 6
NAUTICAL MILES
LIVING POPULATIONS
SPECIMENS / SAMPLE
100 or less
100 - 500
500 - 1000
1000 or more
variable 4 to 700
29° 10'
J.R.M.
89°00'

Fig. 9.—Areal distribution of living population expressed as numbers of specimens per equal volume sample.

TABLE II. DISTRIBUTION OF LIVING FORAMINIFERA IN PER CENT OF TOTAL LIVING POPULATIONS FROM STATIONS 769A–71B

COLLECTION SEASON	NOV. 1955 ("A" SERIES)																											FEB. 1956 ("B" SERIES)																		
STATION	769	770	771	772	773	774	775	776	777	778	779	780	781	783	786	787	788	789	790	791	792	793	794	795	796	797	798	2	3	4	5	6	7	8	60	61	62	63	64	65	66	67	68	69	70	71
DEPTH IN FEET	7	12	15	14	15	15	32	26	21	24	26	25	26	21	36	37	42	54	59	66	84	60	9	12	18	23	24	29	30	26	20	9	7	9	1	5	6	7	6	4	10	8	12	17	15	5
LIVING POPULATION	114	42	94	21	91	691	520	11	2	54	218	97	23	259	459	2400	3479	3556	2812	1323	130	1304	27	103	286	128	45	7	30	230	7	5	28	4	27	40	267	115	55	52	138	31	41	157	21	116
Ammoastuta inepta																																														
Ammobaculites exiguus					1													X	X																								7	1		
Ammoscalaria pseudospiralis	1		6	10									9				X		1	2	17																				1	3	22	1	38	
Ammotium salsum	4	14	10	32	19	7	21	55		11	12	4	4	X	2	X		X		X		1	4	19	21	5	44		10	17	14		4	25	33	33	2	6	2	13	18	24	20	24	14	11
Angulogerina bella																			X	X																										
Bigenerina irregularis																			X	X																										
Bolivina lowmani				5		1	3			28	16	10	4	X	18	21	49	23	25	4	5	3	40	27	3	7				4	29		7	25					2					1		
B. pulchella primitiva																																														
B. striatula	11	7	10		7	2	2	9			1	1		4	1	1	X	X	X																			6	2		9	3		3		
B striatula spinata																				X																										
B spp.																			X	X																		1								
Buccella hannai																																														
Bulimina marginata												1						X	X																											
Buliminella cf. bassendorfensis							1								X	1	1	4	12	12	11	1																			1					
B elegantissima		2		5	4	9	7			2	5	1		2	5	X	1	1	1			X																			1	3	5	3		2
Cassidulina subglobosa																																														
Elphidium delicatulum					2													X	X					1						3	29					5	2		2	2	1			2		4
E discoidale					1																																									
E gunteri	11			5	11	9	11	9	100	41	6	1	4	X	4	1	1	1	1	1	2	X		9	27	16	11		3	3	14				33		26	14	24	29	27	6	2	25		3
E. matagordanum	1																																		18		2	10	9	2	4					
E poeyanum	3				2								4	X	1	X	X	X							X											2	20	26	47		14	3		7		3
E. spp.			1			1	X				1	1					X							1	X	2									4		4	4			1	3		2		
Epistominella vitrea																		1	1		2	2																								
Goudryina exilis						X	X								X		X								X															2						
Guttulina australis																					1																									
Hanzawaia strattoni																		X	X	X	2																									
Haplophragmoides manilaensis																																														
Miliammina fusca																			X				4	2	3	10	7			2							10	3								
Nonion sp.																																														
Nonionella atlantica	1					X													X	X																								1		
N. opima					10	40	25			7	3	20	26		38	49	12	57	43	65	45	93	15								14	20				10								6		2
Nouria polymorphinoides				5														1	1	6	2																									
N. sp.																		1	1	5																						3	2	1		
Palmerinella gardenislandensis			1			X				2	18							X					4	29	22	34	18	57	63	40		20	68	50			X									
Proteonina atlantica																			X	X	2																									
Quinqueloculina cultrata		7	11			1												X	X																						1	3	5			
Q. compta																			X																											
Q. funafutiensis			11	28	7									2	2		X		X																4	2								6	33	
Q spp.	1		1		1	X	X										X	X		1		X													4	2					1					
Reophax nana							1											X	X	X																										
Reussella atlantica																																														
Streblus beccarii vars.	65	55	50	10	31	30	27	27		9	38	59	48	90	29	27	35	8	9	3	9	X	33	12	19	22	18	43	23	28		60	21		4	40	19	21		41	16	46	35	14	10	74
Textularia earlandi																		X																												1
T. mayori																			X																											
Triloculina sidebottomi						X	1				1	1		1		X		X	X	X					4	5	2			2							12	7	5	2	1	3	2			
Trochammina inflata																																														
T. lobata																																								4					5	
Uvigerina parvula																																														
Virgulina complanata																																														
V. pontoni																		X	1																											
V. sp.																																														
V (Virgulinella) pertusa																																														
Other Genera & Species	1	2	1		4	X	1							1		X	X	3	4	1	2															5	2	1	7	4	4			2		

TABLE III. DISTRIBUTION OF LIVING FORAMINIFERA IN PER CENT OF TOTAL LIVING POPULATIONS FROM STATIONS 72-B–MARSH-C

COLLECTION SEASON	("B" SERIES)								NOV. 1956 ("C" SERIES)																																							
STATION	72	80	81	82	83	88	89	90	100	102	103	104	105	106	107	108	109	110	112	114	115	116	117	118	119	120	121	122	123	125	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	MARSH
DEPTH IN FEET	4	30	21	22	25	41	44	66	2	4	3	11	18	22	28	31	21	25	27	35	48	63	82	113	110	107	101	96	66	12	18	12	15	23	34	51	<1	2	1	4	23	30	48	70	70	
LIVING POPULATION	8	110	17	11	33	44	73	233	213	515	13	185	85	74	383	221	58	29	109	175	506	809	2160	2317	1908	1405	8240	1381	224	51	170	133	805	639	417	26	583	131	695	36	998	209	3805	788	1121	162
Ammoastuta inepta									1																																					1
Ammobaculites exiguus										X							2	3		1						X																				1
Ammoscalaria pseudospiralis			35	55	24	2	5									1	2	7					1	X			X																			
Ammotium salsum	12	25	6	27	12	2	1	X	6	6	46	30	18	14	X	47	27	3	4	1	X	X						X		37	1	19	1	1	2	8	7	30	38	52		X	X			30
Angulogerina bella																							X	X																						
Bigenerina irregularis						2	4																X	X																						
Bolivina lowmani						18	12	24		X				3	8	2	17	49	19	19	46	40	5	16	15	10	9	7	71	4	8		9	16	31	4	X	1	X		34	84	61	50	16	
B. pulchella primitiva																									X	X																				
B. striatula		7	6							1		1	2	1	5	2	3		1	1		X						X					X	1	1											
B. striatula spinata																											X																			
B. spp.												X				X								X	X	X	X		1																X	
Buccella hannai																																														
Bulimina marginata													1		1							X	X	X		X							X	X												
Buliminella cf. bassendorfensis								2					2		2					1	1	3	3	19	44	9	25	7	1							4					X		1	1	1	
B. elegantissima		20	6			9	3			X		3	2			4	2		3	21	19	2	1	1	1	X	2	2	2		1		11	8	3	4					X	1	1	2	2	
Cassidulina subglobosa																						X	X	X	X	X	X																X			
Elphidium delicatulum		1								1			1			1														4		9		1	1		56	24	25	3		X				
E. discoidale									X																						X															
E. gunteri	50	19			3			20	30	33	38	11	10	7	15	8	17		4	2	1	1			X		X	X	X	10	12	2	10	5	5	8	X	1	2		3	X	1	X	X	
E. matagordanum									1	1			2		X	2			1										3		2	3	X	2	8			1			X		X			
E. poeyanum									2	1					X			7	2															X												
E. spp.									2			1			1				1			1	X	X		X	X		4				X		1						2					
Epistominella vitrea																				1		1	1	1	1	1	1	1	X						1						2		2	1		
Gaudryina exilis							1			1		1				1		3			X		X	X									X	X												
Guttulina australis							3																																							
Hanzawaia strattoni						2	1																X	X		X																				
Haplophragmoides manilaensis														1																		1														1
Miliammina fusca									6	2		1																		10		8	X				32	28	14		X	7				36
Nonion sp.																			5	33	6	2	X	X		X		X																		
Nonionella atlantica					3	2								1	X						X	X	X	X	X		X							X												
N. opima		20	12	18	12	5	3	48				2		1	9	1	2	7	1	3	18	41	77	56	36	73	58	78	14		2		16	4	4	8					8		31	38	77	
Nouria polymorphinoides																					X		X	X	X		X																		X	
N. sp.																						X	X	X	2	X	1	X															X			
Palmerinella gardenislandensis								X	13	4		2			X															21	46	48	X	X			X	3	14	45	X	3		X		
Proteonina atlantica	12						3																X	X																						
Quinqueloculina cultrata		1	12		3		1		1			2	2				2		3					X							1		X	1									X			
Q. compta						5	8															X																								
Q. funafutiensis					3	9	11									1			1																											
Q. spp.						2				1		X		3	1						X					X			X				X													
Reophax nana		1			3			1				1	1		X		2		4	2	X	X	1	X	X	1	X	X					X	1	1								X			
Reussella atlantica						2																																								
Streblus beccarii vars.		5	12		24	39	30	1	27	48	8	43	46	60	49	24	20	21	42	13	9	7	7	2	1	3	1	3	3	14	16	9	48	60	41	64	3	12	7		50	2	1	4	3	
Textularia earlandi																				1		X	X	X		X	X	X					X		X											
T. mayori																									X																					
Triloculina sidebottomi	25				12		8	3	11		8	2	11		2				8			1		1	X	X	X	1			11	1	1	X	1						1	X	X	X		
Trochammina inflata																																														17
T. lobata			12																																											
Uvigerina parvula																								X																						
Virgulina complanata																								X	1		X																			
V. pontoni																				1			X		X	X	X																			
V. sp.														8	1								X	X		X	1																			
V. (Virgulinella) pertusa																								1		1	X																			
Other Genera & Species		1								1			2	1	6	6	4		1			1	4	3		2	2	1	1				3	X	X		2					3	2	4	1	14

COLLECTION SEASON	NOV. 1955 ("A" SERIES)																							
STATION	769	770	772	773	774	775	777	778	779	780	783	786	787	788	789	790	791	792	793	794	795	796	797	798
DEPTH IN FEET	7	12	14	15	15	32	21	24	26	25	21	36	37	42	54	59	66	84	60	9	12	18	23	24
TOTAL POPULATION	11,500	7200	6300	6000	8700	1600	13,800	7500	1520	1400	850	6000	14,000	25,600	25,000	27,200	32,200	14,600	1600	1100	800	1300	220	2750
Ammoastuta inepta																								
Ammobaculites exiguus							3				X					X	1							
Ammoscalaria pseudospiralis	X		1				X		1	X				X	X		1	1						
Ammotium salsum	5	8	13	12	13	15	6	6	7	2	1	2	1	X	X				X		45	16	4	27
Angulogerina bella																X								
Bigenerina irregularis																X		X						
Bolivina lowmani			X	1		2	3	7	6	5	X	11	6	20	12	14	11	4	2	9	10	2	3	
B. pulchella primitiva																		X						
B. striatula	1	1	1	1	1	1	1		1	X	2		1	X	1			X						
B. striatula spinata															X	X								
B. spp											X				X	X		1	X					
Buccella hannai							1	1			X	3	1	1	X	X		X						
Bulimina marginata														X	1	X		X						
Buliminella cf. bassendorfensis		X									X	1		1	5	5	6	15	1	2	X			
B. elegantissima		1	2	1	2	4	5	6	3	4	1	5	1	4	5	4	1	X	X			X		
Cassidulina subglobosa			X							X	X		1	X	1	1	1	X	X	2				
Elphidium delicatulum														X			1						1	
E. discoidale																1								
E. gunteri	36	35	9	13	16	14	23	23	9	6	9	2	3	4	3	3	3	2	1	9	9	20	18	17
E. matagordanum	1			X		X	4	2		1			1									X	1	
E. poeyanum	1	X	1				1	6		X	3											X		
E. spp.	4	1	4	3	1	X	10	1	2	4	5		1	1	2	2	8	X						
Epistominella vitrea			1	X								1	1	1	4	4	8	21	8	12				
Gaudryina exilis				1						X	X			X		1						X		
Guttulina australis											X													
Hanzawaia strattoni									1	X	1		X		1	1	2	X						
Haplophragmoides manilaensis		X			1						X													
Miliammina fusca	1		1	X	X			X								X				3	1	4	13	5
Nonion sp.			2				5	5	1	1	1	1	3	2	3	4	2	3				1	1	
Nonionella atlantica							X	1		X	X	1	X		1	1	2	X		2				
N. opima				X	6	11	5	4	6	5	1	11	13	9	21	19	15	33	81	8	1	X	X	
Nouria polymorphinoides															X	X								
N. sp.															X		X							
Palmerinella gardenislandensis							X		15										X	8	13	31	32	22
Proteonina atlantica																		X						
Quinqueloculina cultrata		1				X		1		1					X			X						
Q. compta											X		X	1		X	X	X						
Q. funafutiensis				X			1	1	1	1	2	1	X		X	X		X						
Q. spp.	X						1	2	1	1	X	1	X			X	2	1						
Reophax nana					X	1	X			X				1	1	1	2	X						
Reussella atlantica											X													
Streblus beccarii vars	38	50	62	50	45	52	25	26	23	22	60	56	58	42	25	21	25	11	1	34	16	18	16	29
Textularia earlandi						X									2	2	2	1	3		1			
T. mayori																1	X							
Triloculina sidebottomi	11	1	2	15	16	18	1	7	22	44	3	1	8	8	9	5	1	1	2	5	3	7	11	
Trochammina inflata																								
T. lobata	X			1																				
Uvigerina parvula															X			1						
Virgulina complanata																X		X						
V. pontoni													X		X	1	1	X						
V. sp																								
V. (Virgulinella) pertusa																								
Other Genera & Species	2	2	1	2	1	2	5	1	1	3	1	3	1	5	2	9	5	5	1	6	1	1		

COLLECTION SEASON	NOV. 1956 ("C" SERIES)																																			
STATION	100	102	103	104	105	106	107	108	109	110	112	114	115	116	117	118	119	120	121	122	123	125	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142
DEPTH IN FEET	2	4	3	11	18	22	28	31	21	25	27	35	48	63	82	113	110	107	101	96	66	12	18	12	15	23	34	51	< 1	2	1	4	23	30	48	70	70
TOTAL POPULATION	1120	10,200	150	7900	670	260	400	2000	7700	7000	4600	900	2500	3500	34,000	25,000	3400	11,000	8900	2900	300	225	430	640	1700	2300	420	1150	2100	4200	3200	430	1300	600	4400	850	1700
Ammoastuta inepta																																					
Ammobaculites exiguus			1						1								X	X							1		1										
Ammoscalaria pseudospiralis										1					X																						
Ammotium salsum	6	17	7	17	21	12	2	9	6	1	1	1	3						X	X		56	2	20	3	2	3	1	18	65	46	81		5			1
Angulogerina bella															X		X																				
Bigenerina irregularis														X	1	X		1																			
Bolivina lowmani			1	1	7		4	1	1	16	10	12	20	9	3	12	11	12	6	6	36		9		7	7	8		3	X		4	33	45	58	13	14
B. pulchella primitiva										1				1	1	X																					
B. striatula			3	1		6	6	1	2	1	2	3	1		X					1					1	1											
B. striatula spinata															X																						
B. spp										3				1	1	1		1	1																		X
Buccella hannai									1	1	2	1	1	X	X		X											1									
Bulimina marginata									X		X					X		1																			
Buliminella cf. bassendorfensis										1	X		1	4	8	9	28	10	16	7		4			1	1		1							1	1	3
B. elegantissima		1			2			2	6	7	4	18	13	7	1	4	2	3	5	4	1				8	4	2	1	2		1		1	3	1	2	4
Cassidulina subglobosa											X			X	1	1	2	1	1														1	3			
Elphidium delicatulum	4	X																						22		3			45	14	20						
E. discoidale									X	2																											
E. gunteri	21	27	37	24	12	40	20	16	23	17	4	2	4	2	5	1	1	1	2	4	7		2	2	19	9	10	14		1	2		5		X	1	4
E. matagordanum	3	1	2						1	1													4			1											
E. poeyanum	3			X				3		9	2			1	X											X											
E. spp.	3	2	2	5	2		2	1	5	4	4	1	2	2	2	1	1	2			4		6		1	1	1									X	
Epistominella vitrea											X	1		3	4	14	7	11	14	4						X	X	3					2	3	3	1	1
Gaudryina exilis		X		X					X				1	X	X			X			1					X		1									
Guttulina australis																																					
Hanzawaia strattoni										1					X	1	1	1																			
Haplophragmoides manilaensis	3																													X							1
Miliammina fusca	6	2	1	1																		7	4	15					18	11	15				X		
Nonion sp.		1		3	2			1	4	5	7	10	4	4	3	3	1	3	3	3					X	2	3	5		3	1		4	3	X	X	2
Nonionella atlantica	1									1				1	2	1	1	X															1				
N. opima			1	X				3	8	4	6	2	9	19	21	30	34	30	36	37	21	4			11	2	17	7					10	3	29	40	51
Nouria polymorphinoides									X																												X
N. sp.																																					
Palmerinella gardenislandensis	13	1	2	1			12							X								11	43	15							5	15	2	8			
Proteonina atlantica																																					
Quinqueloculina cultrata	1			X							X			X												1											X
Q. compta										X							1										X										
Q. funafutiensis								1	X																												
Q. spp.	1							2	1	1	1			1	1	X	X	X					2			X		3									1
Reophax nana					2			1	X			1	1	X	X		X	1		X					1	1	1									X	
Reussella atlantica											1																X										
Streblus beccarii vars	20	46	42	40	27	24	48	55	28	19	41	46	40	32	40	8	6	8	8	29	21	18	13	18	36	50	36	46	5	5	10		34	21	3	7	13
Textularia earlandi				1	5									X		1	1	5	2		1				1	X	X										
T. mayori																																					
Triloculina sidebottomi	14	1		3	20	9	4	3	11	3	11			3		7	3		4	3	7		15	2	9	13	16	14					1	5	2	4	5
Trochammina inflata									X																												
T. lobata											X				X																						
Uvigerina parvula															X	X	X																2				
Virgulina complanata														X	X																						
V. pontoni												1			2	1	X	X									X										
V. sp						9									X	X	X		X								X								X		
V. (Virgulinella) pertusa														1	X	X	X		X																		
Other Genera & Species	1	1	1	3			2	1		1	4	1		9	4	6		9	2	2	1			6	1	2	2	1	9	1			4	1	5	1	

dence of marginal or adverse life conditions. It is concluded that a species has the smallest average size where the environmental factors are optimum and the largest size where conditions are most rigorous.

This concept agrees with the experimental results of Bradshaw (1957) who successfully cultured *Streblus beccarii* var. *tepida* under various conditions of temperature and salinity. He was able to establish temperature and salinity limits for growth and reproduction beyond which the species ceased to flourish or was killed. In general, the specimens of *S. beccarii* var. *tepida* reached reproductive maturity most rapidly and with a minimum average size at a salinity of 30°/oo and temperature of 24°–30°C. Cultures grown at greater or less temperature and salinity values reproduced more slowly and attained a greater average size.

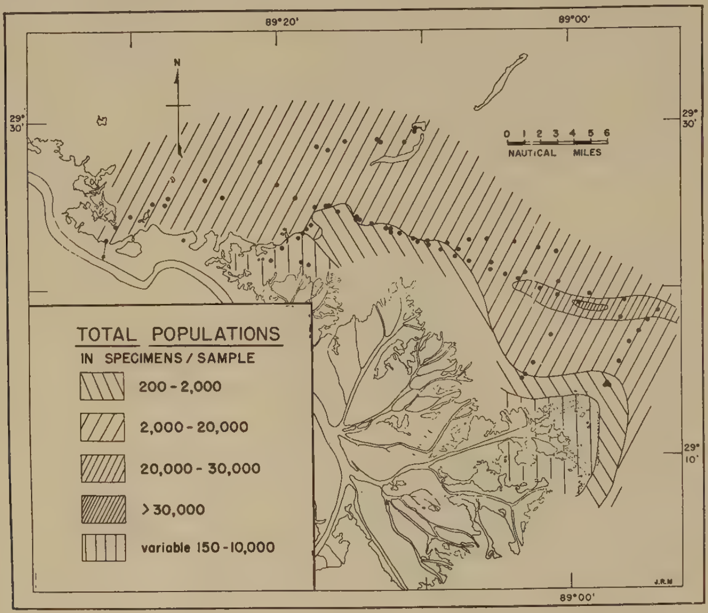

Fig. 10.—Areal distribution of total population (living plus dead) expressed as numbers of specimens per equal volume sample.

Total Foraminifera.—The distribution of the total populations (living plus dead specimens) for two collection periods is given in Figure 10. A zone of maximum total population size occurs on the bottomset beds (Fig. 4) but it is displaced farther seaward than the zone of maximum living populations. The shelf and sound areas contain relatively large total populations but the lowest average living populations. In addition, the smallest total counts occur on the shallow pro-delta slope (Fig. 4) which supports an intermediate size standing crop.

On the pro-delta slope most of the total population is composed of living specimens. Two cores about 1½ feet long were collected at Station 123-c, off North Pass, and Station 140-c, off Pass a Loutre. Each core was cut into samples 2 cm. thick and the total number of Foraminifera in each sample was counted. The total population in both cores in the surface sample was comparable with the area average, approximately 1,400 specimens per 10 ml. of sediment. Below the surface the average population was approximately 25 per cent of the surface count. The quantity of specimens varied with depth in the cores. Thin, high population zones were separated by relatively thick low population zones. The population peaks in the North Pass core were approximately 20 cm. apart and in the Pass a Loutre core 8–9 cm. apart. This may result from seasonal variations of river discharge and sedimentation rates on the pro-delta slope.

These data indicate that the living Foraminifera at the sediment-water interface may keep from being buried by crawling up through the fall of detritus. Total population counts from the top centimeter in rapidly sedimenting areas therefore may be four or more times larger than the number of specimens actually contributed to the sedimentary column. Analyses of cores in this area indicate that Foraminifera tests constitute only a very small percentage of the sediment (Shepard, 1956).

Samples from the fluvial marine and interdistributary bay environments have highly variable total populations ranging from 150 to 10,000 Foraminifera per sample. There is no apparent distribution pattern.

The species compositions of the living and total counts were similar with few exceptions. The most interesting exception occurred in Blind Bay just south of Pass a Loutre. Rare specimens of species not previously found in shallow water were encountered in the total population counts in several samples from the outer edge of the bay; no specimens were living. Field observations indicate that the deep-water fauna is being eroded from the mud-lump islands and reworked into the interdistributary bay sediments and fauna.

Andersen (1951) made a survey of the foraminiferal faunas contained in several mud lumps in the southern delta and noted that older specimens were reworked into adjacent sediments. Andersen compared the mud-lump faunas with modern assemblages from surface sediment samples and estimated as much as 400–450 feet of vertical displacement of a mud-lump sample near South Pass. Other samples contained faunas typical of depths much less than 400 feet.

Material collected during this study from a small mud lump near Pass a Loutre (Station 143-c) contained a rich microfauna, including the following Foraminifera.

Benthonic Species

Angulogerina bella Phleger and Parker
Bigenerina irregularis Phleger and Parker
B. textularioidea (Goës)
Bolivina barbata Phleger and Parker
B. lowmani Phleger and Parker
B. pulchella primitiva Cushman
B. striatula spinata Cushman
B. subaenariensis mexicana Cushman
B. subspinescens Cushman
Buccella hannai (Phleger and Parker)
Bulimina marginata d'Orbigny
Buliminella cf. *B. bassendorfensis* Cushman and Parker

Cancris oblonga (Williamson)
Cassidulinoides tenuis Phleger and Parker
Cibicides aff. *C. floridanus* (Cushman)
C. mollis Phleger and Parker
Elphidium discoidale (d'Orbigny)
E. incertum mexicanum Kornfeld
Epistominella exigua (Brady)
E. vitrea Parker
Gaudryina cf. *G. aequa* Cushman
Globobulimina mississippiensis Parker
Hanzawaia concentrica (Cushman)
H. strattoni (Applin)
Höglundina elegans (d'Orbigny)
Nodosariidæ (others)
Lenticulina peregrina (Schwager)
Marginulina marginulinoides (Goës)
Miliolidae (others)
Nodobaculariella cassis (d'Orbigny)
Nonionella atlantica Cushman
N. opima Cushman
Planulina exorna Phleger and Parker
Pseudoclavulina mexicana (Cushman)
Pseudoeponides umbonatus (Reuss)
Pyrgo comatus (Brady)
P. cf. *P. nasutus* Cushman
Quinqueloculina horrida Cushman
Q. lamarckiana d'Orbigny
Rectobolivina advena (Cushman)
Rectuvigerina nicoli Matthews
Reussella atlantica Cushman
Robulus calcar (Linné)
Rotaliidae (others)
Sigmoilina distorta Phleger and Parker
Siphonina bradyana Cushman
Spiroloculina antillarum d'Orbigny
Streblus beccarri (Linné) vars.
Textularia mayori Cushman
Triloculina cf. *T. brevidentata* Cushman
T. tricarinata d'Orbigny
Uvigerina parvula Cushman
Virgulina complanata Egger
V. mexicana Cushman
V. pontoni Cushman
Valvulineria mexicana Parker

Planktonic Species

Globigerina bulloides d'Orbigny
G. eggeri Rhumbler
Globigerinella aequilateralis (Brady)
Globigerinita glutinata (Egger)
Globigerionoides conglobatus (Brady)
G. ruber (d'Orbigny)
G. sacculifer (Brady)
Globorotalia menardii (d'Orbigny)
G. truncatulinoides (d'Orbigny)
G. tumida (Brady)
Orbulina universa d'Orbigny
Pulleniatina obliquiloculata (Parker and Jones)

Comparison of the mud-lump fauna with modern Foraminifera depth assemblages in the northern Gulf indicates a depth of deposition equivalent to the present outer continental shelf, between 180 and 360 feet.

The formation of mud lumps apparently is not restricted to the present. In a number of borings described by Shepard and Lankford (1959) which penetrated shallow bay deposits, relatively deep-water Foraminifera were found associated with a more abundant interdistributary bay assemblage. They are believed to have been reworked from older mud lumps.

It may be concluded that the depth of origin of mud-lump sediments varies considerably, that no single sedimentary unit is the subsurface source of these piercement structures, and that deep-water deposits may be displaced vertically and reworked into shallow-water sediment of the same approximate geologic age.

Living/Total ratios.—The effect of sediment dilution may be shown by comparing the number of living specimens of Foraminifera with the total number of specimens in a sample. These are expressed as percentage ratios (Fig. 11). The high living/total ratios, from 25 per cent to more than 90 per cent, occur in the deltaic marine environment where deposition is most rapid. There is a small decrease in the ratios upslope to the delta platform (Fig. 3) and a larger decrease on the open shelf and in Breton Sound where deposition rates are much smaller. The living populations in the sound and open Gulf are less than 10 per cent of the total population and frequently are less than 1 per cent. This offshore decrease in ratios agrees with the results of Parker (1954, Table 2) and Phleger (1955, Fig. 11) in the same area. Ratios in the interdistributary bay and fluvial marine environ-

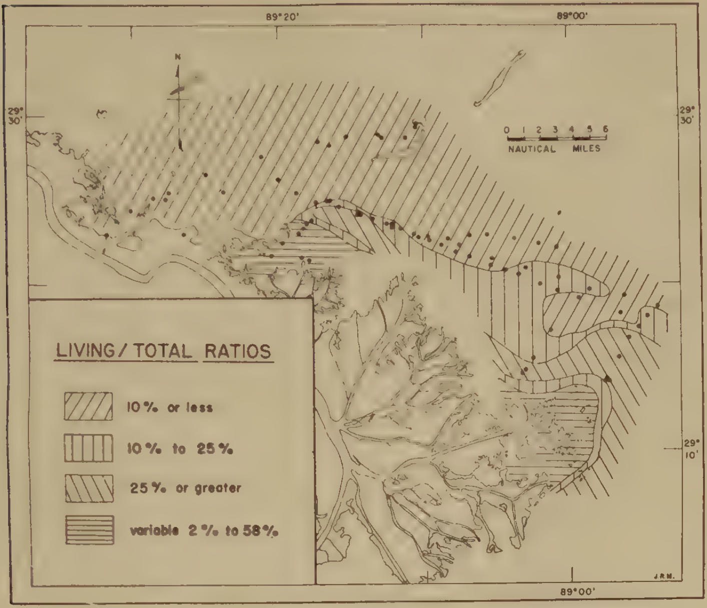

Fig. 11.—Areal distribution of ratios of living populations to total populations (living plus dead) expressed as per cent.

ments vary between 2 per cent and 58 per cent and, like the living and total populations in these two environments, have no obvious distribution pattern.

Discussion

The most striking characteristic of the faunal pattern is its areal complexity. The distribution of assemblages approximately coincides with the distribution of water and sediment types. The degree of variability of sediment and water types appears to be the most important ecological factor. No single variable appears to be the controlling ecologic factor.

The deltaic marine and open shelf assemblages occur in an essentially marine environment. The species of both faunas are widespread on the shallow shelf of the northern Gulf of Mexico and, with a few exceptions, are indicative of normal marine conditions. A few species, including *Streblus beccarii* and *Elphidium gunteri*, are found also in various marginal marine environments of the Gulf Coast and appear to have a much wider tolerance of environmental variation than the restricted marine species.

The distribution of these two open-ocean assemblages coincides with distribution of the Gulf water mass. This water is characterized by nearly constant salinity and pH values and has relatively small fluctuations in temperature. Near the delta, and especially off the major distributaries, the undiluted Gulf water contains sediment derived from the river. The submarine extent of the river-borne detritus, consisting of fine-grained and poorly sorted silts and clays, is shown in Figure 5-a. The boundary between these sediments and the somewhat coarser, better sorted material offshore is transitional and coincides with the gradational boundary between the deltaic marine and open-shelf assemblages. It is probable that the characteristics of the deltaic marine fauna, which differentiate it from the open-shelf fauna, are related to the higher sedimentation rates in the deltaic marine environment.

The usual effect of increasing sedimentation rates is to dilute or decrease the quantity of Foraminifera in a volume of sediment. Any change in the quantity of Foraminifera with time may reflect a change in the rate of sediment accumulation. This is true only as long as foraminiferal production, the number of tests produced within an area and unit of time, remains constant. The distribution of living populations indicates, however, that production is not constant in all sedimentary environments. The deltaic marine assemblage is defined by its very large standing crop dominated by two or three species and high living/total ratios. It occurs in the rapidly prograding delta where deposition is most rapid. Due to high foraminiferal productivity, the total number of Foraminifera in this environment may be several times larger than on the open shelf where sedimentation rates are considerably less.

The reasons for high production in areas influenced by river discharge and relatively rapid sedimentation are not known. There are several features associated with river effluents which may be important. These are concentrations of nutrients and trace elements, from soils in the Mississippi drainage; large bacterial populations adhering to the surfaces of the finely divided detritus and which may be used as food; and abundance of organic solids. Laboratory culture experiments are needed to evaluate these possibilities.

There may be an upper limit to the benefits directly or indirectly associated with rapid deposition; too much sedimentation may have a smothering effect. The smallest populations in the area occur just seaward of the passes where sediment accumulation has been estimated at 1 foot per year. The small population here is composed almost entirely of living specimens. The fewer species found in the deltaic marine environment compared with the larger number characteristic of the open shelf probably is due to higher deposition rates. Many Foraminifera are unable to adapt to the ecological conditions prevailing and thus are excluded. Other species, principally *Bolivina lowmani*, *Buliminella* cf. *B. bassendorfensis*, and *Nonionella opima*, apparently thrive in the deltaic marine environment and account for the abnormally large standing crops. A similar situation has been observed in the delta of the Guadalupe River, San Antonio Bay, Texas, where three species constituted more than 95 per cent of the abnormally large living population (Phleger and Lankford, 1957).

The sound fauna is characteristic of Gulf coast bays and sounds having continual or periodic influxes of fresh water. The sound water mass is characterized by intermediate salinities, variable temperatures, and suspended sediment stirred up from the bottom. Some of the sound species, such as *Ammotium salsum*, *Bolivina striatula*, and *Elphibium matagordanum*, apparently have adapted to the marginal marine conditions and are found only rarely in the normal marine environment. A second and more abundant species group is common in the sound association but is found also in abundance in the near-shore open-shelf assemblage and more rarely in the deltaic marine fauna. These species are *Buliminella elegantissima*, *Elphidium gunteri*, *E. poeyanum*, *Streblus beccarii*, and *Triloculina sidebottomi*. The apparent adaptability of these species may explain their abundance in areas subject to rigorous and wide environmental changes.

Mixing of sound and open-shelf species frequently occurs in inlets and adjacent areas (Parker *et al.*, 1953, p. 17; Phleger, 1954, p. 604). The width of the mixed zone is related to the depth of the inlet and to the thickness of the less dense sound water. This water thickness is a function of vertical mixing of the water column, movement by tidal and wind currents, and supply of fresh water. Samples from the rapidly sedimenting pro-delta slope prograding into the inlet between Breton Island and the delta contain a fauna with both sound and deltaic marine characteristics. This is thought to result from the high rate of deposition occurring in water alternating between the sound and Gulf types.

The bottom waters of the marsh, interdistributary bay, and fluvial marine environments are characterized by rapid and extreme changes in chemical and physical properties; each has its own pattern of variation described on page 2072. Two species, *Ammotium salsum* and *Miliammina fusca*, are found in all three environments and are able to withstand a wide range of conditions. Other forms are more selective. *Palmerinella gardenislandensis*, for example, apparently requires a highly variable salinity and is most abundant in the fluvial marine assemblage. *Elphidium delicatulum*, however, is found in several salinity regimes but is best adapted to the very shallow interdistributary bays which have wide temperature ranges.

There is a general coincidence of sediment characteristics (Figs. 4, 5, and 6) and the faunal associations (Fig. 8). With the exception of the deltaic marine environment, it is believed that there is no causal relation between sediment and fauna. It is thought that both are the effects of complex oceanographic processes which produce independent faunal and sedimentary environments.

Much of the Tertiary and Quaternary deposition in the Gulf Coast geosyncline is thought to have had a deltaic origin with rapid facies changes both vertically and horizontally. The ecologic criteria developed from study of Recent Foraminifera in the Mississippi Delta should be useful for interpreting the complex stratigraphy of ancient delta deposits. These criteria have been applied with success to relatively modern sediments in southern Louisiana by Shepard and Lankford (1959). The Foraminifera in samples from a series of borings in the modern birdfoot delta were studied. It was possible to identify and use the faunal associations defined in the present report to interpret the depositional history of several Quaternary delta sequences. It is expected that these faunal criteria would apply on a species level to the late Tertiary of the Gulf Coast since relatively few species have become extinct since the upper Miocene. It should be possible to extend these concepts back to the Eocene by using the quantitative aspects of these data in addition to those species which are similar or closely related to modern forms.

REFERENCES

Andersen, H. V., 1951, "Report on the Mudlumps at the Mouths of the Mississippi River: Part II, Foraminiferal Faunules from the Mudlumps and Environments in the Vicinity of the Mouths of the Mississippi River," unpublished report, *New Orleans District, Corps of Engineers.* 214 pp.

Bandy, Orville L., 1954, "Distribution of Some Shallow-Water Foraminifera in the Gulf of Mexico," *U. S. Geol. Survey Prof. Paper 254-F.*

———, 1956, "Ecology of Foraminifera in Northeastern Gulf of Mexico," *ibid., Prof. Paper* 274-G.

Boltovskoy, Esteban, 1957, "Los Foraminiferos del Estuario del Rio de la Plata y su Zona de Influencia," *Rev. Instit. Nac. Invest. Ciencias Nat. Museo Argentino Ciencias Nat. "Bernardino Rividavia," Ciencias Geol.*, Vol. 6, No. 1, pp. 1–77.

Bradshaw, John S., 1957, "Laboratory Studies of Growth of the Foraminifer, *Streblus beccarii* (Linné) var. *tepida* Cushman," *Jour. Paleon.*, Vol. 31, No. 6, pp. 1138–47.

Butler, Phillip A., 1952, "Effect of Floodwaters on Oysters in Mississippi Sound in 1950," *Fish and Wildlife Service, Dept. of Interior, Research Rept. 31.* 20 pp.

Geyer, Richard A., 1955, "Effect of the Gulf of Mexico and Mississippi River on the Hydrography of Redfish Bay and Blind Bay," *Pub. Inst. Mar. Sci.*, Vol. IV, No. 1, pp. 155–68.

Inman, D. L., and Chamberlain, T. K., 1955, "Particle-Size Distribution in Nearshore Sediments," in "Finding Ancient Shorelines," *Soc. Econ. Paleon. and Mineral. Spec. Pub. 3*, pp. 106–27.

Kornfeld, M. M., 1931, "Recent Littoral Foraminifera from Texas and Louisiana," *Contr. Dept. Geol. Stanford Univ.*, Vol. 1, No. 3, pp. 77–101.

Lowman, Shepard W., 1949, "Sedimentary Facies in the Gulf Coast," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 33, No. 12, pp. 1939–97.

Ludwick, John C., and Walton, William R., 1957, "Shelf-Edge Calcareous Prominences in Northestern Gulf of Mexico," *ibid.*, Vol. 41, No. 9, pp. 2054–2101.

Parker, Frances L., 1954, "Distribution of the Foraminifera in the Northeastern Gulf of Mexico," *Bull. Mus. Comp. Zool.*, Vol. 111, No. 10, pp. 454–588.

———, Phleger, Fred B, and Peirson, J. F., 1953, "Ecology of Foraminifera from San Antonio Bay and Environs, Southwest Texas," *Cushman Found. Foram. Res. Spec. Pub. 2.* 75 pp.

Phleger, Fred B, 1951, "Ecology of Foraminifera, Northwest Gulf of Mexico. Part 1, Foraminifera Distribution," *Geol. Soc. America Mem. 46.* 88 pp.

———, 1954, "Ecology of Foraminifera and Associated Micro-Organisms from Mississippi Sound and Environs," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 38, No. 4, pp. 584–647.

———, 1955, "Ecology of Foraminifera in Southeastern Mississippi Delta Area," *ibid.*, Vol. 39, No. 5, pp. 712–52.

———, 1956, "Significance of Living Foraminiferal Populations Along the Central Texas Coast," *Contr. Cushman Found. Foram. Res.*, Vol. VII, Pt. 4, pp. 106–51.

———, and Lankford, Robert R., 1957, "Seasonal Occurrences of Living Bethonic Foraminifera in Some Texas Bays," *ibid.*, Vol. VIII, Pt. 3, pp.93–105.

Phleger, Fred B, and Parker, F. L., 1951, "Ecology of Foraminifera, Northwest Gulf of Mexico. Part 2, Foraminifera Species," *Geol. Soc. America Mem. 46.* 64 pp.

Scruton, P. C., 1955, "Sediments of the Eastern Mississippi Delta," in "Finding Ancient Shorelines," *Soc. Econ. Paleon. and Mineral. Spec. Pub. 3*, pp. 21–50.

———, 1956, "Oceanography of Mississippi Delta Sedimentary Environments," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 40, No. 12, pp. 2864–2952.

Shepard, Francis P., 1956, "Marginal Sediments of the Mississippi Delta," *ibid.*, Vol. 40, No. 11, pp. 2537–2623.

———, and Lankford, Robert R., 1959, "Sedimentary Facies from Shallow Borings in Lower Mississippi Delta," *ibid.*, Vol. 43, No. 9, pp. 2051–67.

Stewart, Harris B., 1956, "Sediments and the Environments of Deposition in a Coastal Lagoon," doctoral dissertation, Univ. California, Los Angeles. 355 pp.

Todd, Ruth, and Bronnimann, Paul, 1957, "Recent Foraminifera and Theocamoebina from the Eastern Gulf of Paria," *Cushman Found. Foram. Res. Spec. Pub. 3.* 43 pp.

TREADWELL, ROBERT C., 1955, "Sedimentology and Ecology of Southwest Coastal Louisiana," in "Trafficability and Navigability of Delta-Type Coasts. Trafficability and Navigability of Louisiana Coastal Marshes," *Louisiana State Univ. Tech. Rept. 6.* 78 pp.

WALTON, W. R., 1952, "Techniques for Recognition of Living Foraminifera," *Contr. Cushman Found. Foram. Res.*, Vol. III, Pt. 2, pp. 56–60.

WARREN, A. D., 1957, "Foraminifera of the Buras-Scofield Bayou Region, Southeast Louisiana," *ibid.*, Vol. VIII, Pt. 1, pp. 29–40.

ZOBELL, CLAUDE E., 1946, "Redox Potentials of Marine Sediments," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 30, No. 4, pp. 477–513.

FAUNAL REFERENCE LIST

Ammoastuta inepta (Cushman and McCulloch) (Pl. 1, Fig. 4); *Ammobaculites ineptus*, 1939, Allan Hancock Exped., Vol. 6, No. 1, p. 89, Pl. 7, Fig. 6. Restricted to the marsh fauna; very rare dead specimens found in adjacent faunas.

Ammobaculites exiguus Cushman and Bronnimann (Pl. 1, Fig. 9); 1948, Contr. Cushman Lab. Foram. Res., Vol. 24, Pt. 2, p. 38, Pl. 7, Figs. 7, 8. Has been found living in low frequencies in the sound and more rarely in deltaic marine fauna.

Ammoscalaria pseudospiralis (Williamson) (Pl. 1, Figs. 5–7); *Proteonina pseudospiralis*, 1858, Rec. Foram. Great Britain, p. 2, Pl. 1, Figs. 1, 2. Occurs in sound and deltaic marine assemblages and rarely in open-shelf fauna. Considerable range of variation in length-width ratio of this species.

Ammotium salsum (Cushman and Bronnimann) variants (Pl. 1, Fig. 8); *Ammobaculites salsus*, 1948, Contr. Cushman Lab. Foram. Res., Vol. 24, Pt. 1, p. 16, Pl. 3, Figs. 7–9. Found in large frequencies in marsh, interdistributary bay, fluvial marine, and sound assemblages. Seems to be restricted to environments characterized by highly variable ecologic water masses; not found in open-shelf fauna and only rarely in deltaic marine fauna.

Angulogerina bella Phleger and Parker (Pl. 3, Fig. 8); 1951, Geol. Soc. America Mem. 46, Pt. 2, p. 12, Pl. 6, Figs. 7, 8. Occurs only in open-shelf assemblage.

Arenoparrella mexicana (Kornfeld) (Pl. 1, Figs. 20a–c); *Trochammina inflata* (Montagu) var. *mexicana*, 1931, Contr. Stanford Geol. Dept., Vol. 1, p. 86, Pl. 13, Figs. 5a–c. Found primarily in marsh fauna but occasionally found in low frequencies in adjacent environments.

Bigenerina irregularis Phleger and Parker (Pl. 1, Fig. 12); 1951, Geol. Soc. America Mem. 46, Pt. 2, p. 4, Pl. 1, Figs. 16–21. Occurs in low frequencies in open-shelf fauna.

Bolivina lowmani Phleger and Parker (Pl. 3, Fig. 4); 1951, Geol. Soc. America Mem. 46, Pt. 2, p. 13, Pl. 6, Figs. 20a, b, 21. Characteristically abundant in deltaic marine fauna and occurs in much lower frequencies in open-shelf assemblage; found also in mixed zones between deltaic marine environment and the sound, fluvial marine, and interdistributary bay environments.

Bolivina pulchella primitiva Cushman (Pl. 3, Fig. 7); *Bolivina pulchella* (d'Orbigny) var. *primitiva*, 1930, Florida State Geol. Surv. Bull. 4, p. 47, Pl. 8, Figs. 12a, b. Found only in open-shelf fauna.

Bolivina striatula Cushman (Pl. 3, Fig. 6); 1922, Carnegie Inst. Washington Publ. 311, p. 27, Pl. 3, Fig. 10. This is one of the species limited to the sound fauna; occurs in relatively low frequencies.

Bolivina striatula spinata Cushman (Pl. 3, Fig. 5); *Bolivina striatula* Cushman var. *spinata*, 1936, Spec. Publ. 6, Cushman Lab. Foram. Res., p. 59, Pl. 8, Figs. 9a, b. Has been found in low frequencies in open-shelf and deltaic marine assemblages.

Buccella hannai (Phleger and Parker) (Pl. 3, Figs. 11a, b); *Eponides hannai*, 1951, Geol. Soc. America Mem. 46, Pt. 2, p. 21, Pl. 10, Figs. 11a, b, 12a, b, 13a, b, 14a, b. Has not been found living; occurs in dead population of open-shelf fauna and occasionally in deltaic marine samples.

Bulimina marginata d'Orbigny (Pl. 2, Fig. 14); 1826, Ann. Sci. Nat., Vol. 7, p. 269, No. 4, Pl. 12, Figs. 10–12. In frequencies of 1 per cent or less in sound and deltaic marine faunas.

Buliminella cf. *B. bassendorfensis* Cushman and Parker (Pl. 2, Fig. 15); 1937, Contr. Cushman Lab. Foram. Res., Vol. 13, Pt. 1, p. 40, Pl. 4, Figs. 13a, b. In high frequencies is characteristic of deltaic marine fauna; occurs in low frequencies in open-shelf fauna and in zones of mixing between neighboring assemblages.

Buliminella elegantissima (d'Orbigny) (Pl. 2, Fig. 16); *Bulimina elegantissima*, 1839, Voy. Amér. Mérid., Vol. 5, Pt. 5, "Foraminifères," p. 51, Pl. 7, Figs. 13, 14. Widespread distribution in sound, deltaic marine, and open-shelf faunas.

Cassidulina subglobosa Brady variant (Pl. 3, Fig. 15); 1881, Quart. Journ. Micr. Sci., n. s., Vol. 21, p. 60; 1884, Rept. Voy. Challenger, Zool., Vol. 9, p. 430, Pl. 54, Figs. 17a–c. In frequencies of less than 1 per cent in deltaic marine assemblage.

Elphidium delicatulum Bermudez (Pl. 2, Fig. 9); 1949, Spec. Publ. 25, Cushman Lab. Foram. Res., p. 168, Pl. 11, Figs. 22, 23. In abundance, this species typifies interdistributary bay fauna; found in lower frequencies in fluvial marine fauna and only sporadically in sound fauna.

Elphidium discoidale (d'Orbigny) (Pl. 2, Fig. 6); *Polystomella discoidale*, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 56, Pl. 6, Figs. 23–24. Reported living by Phleger

(1955) from open-shelf environment; found in very low frequencies in this investigation in sound and deltaic marine faunas.

Elphidium gunteri Cole (Pl. 2, Figs. 7a, b); 1931, Florida State Geol. Surv. Bull. 6, p. 34, Pl. 4, Figs. 9–10. In east Delta area, this is one of the most widespread species; occurs in abundance in interdistributary bay, fluvial marine, and sound faunas and in lower frequencies in deltaic marine and open-shelf faunas.

Elphidium matagorianum (Kornfeld) (Pl. 2, Figs. 8a, b); *Nonion depressula* (Walker and Jacob) var. *matagordanum*, 1931, Contr. Dept. Geol. Stanford Univ., Vol. 1, No. 3, p. 87, Pl. 13, Figs. 2a, b. Typically in sound fauna.

Elphidium poeyanum (d'Orbigny) (Pl. 2, Figs. 5a, b); *Polystomella poeyana*, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminfères," p. 55, Pl. 6, Figs. 25–26. Most abundantly in sound assemblage.

Epistominella vitrea Parker (Pl. 3, Figs. 14a, b); 1953, Spec. Publ. 2, Cushman Found. Foram. Res., p. 9, Pl. 4, Figs. 34–36, 40, 41. Consistently in low frequencies in living population and slightly higher frequencies in total population of deltaic marine fauna; occurs also in open-shelf fauna, and erratically in sound fauna.

Gaudryina exilis Cushman and Bronnimann (Pl. 1, Fig. 13); 1948, Contr. Cushman Lab. Foram. Res., Vol. 24, Pt. 2, p. 40, Pl. 7, Figs. 15, 16. In low frequencies in sound fauna and very rarely in zone of mixing between sound and deltaic marine assemblages.

Guttulina australis (d'Orbigny) (Pl. 2, Fig. 3); *Globulina australis*, 1839, Voy. Amér. Mérid., Vol. 5, Pt. 5, "Foraminifères," p. 60, Pl. 1, Figs. 1–4. In low frequencies in open-shelf and deltaic marine faunas.

Hanzawaia strattoni (Applin) (Pl. 3, Figs. 16a–c); *Truncatulina americana* Cushman var. *strattoni*, in Applin, Ellisor, and Kniker, Amer. Assoc. Petrol. Geol., Vol. 9, No. 1, p. 99, Pl. 3, Fig. 3. Specimens usually small; immature specimens of *Hanzawaia concentrica* (Cushman) may have been included in the counts. This species occurs in open-shelf assemblage and in zone of mixing between open-shelf and deltaic marine faunas.

Haplophragmoides manilaensis Andersen (Pl. 1, Fig. 3); 1953, Contr. Cushman Found. Foram. Res., Vol. IV, Pt. 1, p. 22, Pl. 4, Figs. 8a, b. Very rare specimens have been found in the marsh and in sound samples bordering the marsh.

Lagenammina atlantica (Cushman) (Pl. 1, Fig. 1); *Proteonina atlantica*, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 5, Pl. 1, Fig. 4. In low frequencies in open-shelf and deltaic marine faunas.

Miliammina fusca (Brady) (Pl. 1, Fig. 18); *Quinqueloculina fusca*, 1870, Ann. Mag. Nat. Hist., Ser. 4, Vol. 6, p. 47 (286), Pl. 11, Figs. 2a–c, 3. Most abundant in marsh and interdistributary bay faunas and somewhat less abundant in fluvial marine assemblage; samples in sound near marshes contain rare specimens of this species.

Nonion sp. (Pl. 2, Figs. 4a, b). Resembles species of genus *Protelphidium*. However, the wall structure was found to have the granular texture of *Nonion* rather than radiate texture of *Protelphidium* or *Elphidium*. It most resembles *Elphidium matagordanum* (Kornfeld) but differs in wall textures, attains a greater maximum diameter, and, axially, is more compressed. Occurs principally in deltaic marine fauna but also is found in low frequencies in sound and interdistributary bay assemblages.

Nonionella atlantica Cushman (Pl. 2, Figs. 13a, b); 1947, Contr. Cushman Lab. Foram. Res., Vol. 23, Pt. 4, p. 90, Pl. 20, Figs. 1–3. Most abundant in open-shelf environment but found rarely in deltaic marine environment.

Nonionella opima Cushman (Pl. 2, Figs. 10–12); Contr. Cushman Lab. Foram. Res., Vol. 23, Pt. 4, p. 90, Pl. 20, Figs. 1–3. Considerable variation in size, shape, and degree of chamber inflation of this species. However, by gradually breaking away the chambers of non-typical specimens, the typical form is soon reached; among smaller forms, there is relatively little variation in form. Occurs very abundantly in deltaic marine assemblage and in lower frequencies in sound and fluvial marine environments where they mix with deltaic marine environment.

Nouria polymorphinoides Heron-Allen and Earland (Pl. 2, Fig. 1); 1914, Trans. Zool. Soc. London, Vol. 20, Pt. 12, p. 376, Pl. 37, Figs. 1–15. In low frequencies in deltaic marine fauna.

Nouria sp. (Pl. 2, Fig. 2). Specimens belonging to *Nouria* occur in deltaic marine assemblage in low frequencies.

Palmerinella gardenislandensis (Akers) (Pl. 3, Figs. 17a–c); *Eponidella gardenislandensis*, 1952, Jour. Paleontology, Vol. 26, No. 4, p. 648, Text Figs. 2a–c. Apertural characteristics show continuous variation ranging from an *Eponidella* aperture to a *Palmerinella* aperture in larger specimens. This range of variation observed in living population of a single sample; in some samples that show this, either the *Eponidella* or the *Palmerinella* type of aperture predominates depending on locality, the former in fluvial marine environment where the species is most abundant, the latter in interdistributary bay where occurrence is sporadic. It is concluded that the morphologic differences are ecotypic, that the species reaches reproductive maturity at an earlier developmental stage in fluvial marine environment where conditions support greatest numbers, and at later stage in interdistributary bays where life conditions appear to be marginal. Species thought to belong to genus *Palmerinella* rather than to *Eponidella* to which it was originally referred by Akers.

Quinqueloculina compta Cushman (Pl. 1, Fig. 14); 1947, Contr. Cushman Lab. Foram. Res., Vol. 23, Pt. 4, p. 87, Pl. 19, Fig. 2. Characteristic of open-shelf environment and found only rarely in sound and deltaic marine assemblages.

Quinqueloculina cultrata (Brady) (Pl. 1, Fig. 15); *Miliolina cultrata*, 1881, Quart. Journ. Micr. Sci., Vol. 21, p. 45; 1884, Rept. Voy. Challenger, Zool., Vol. 9, p. 161, Pl. 5, Figs. 1, 2. Most abundant in sound fauna but also is found in low frequencies in deltaic marine fauna and very rarely in fluvial marine assemblage.

Quinqueloculina funafutiensis (Chapman) (Pl. 1, Fig. 16); *Miliolina funafutiensis*, 1900, Journ. Linn. Soc. Zool., Vol. 28, p. 178, Pl. 19, Fig. 6. Most abundant in sound fauna but occurs also in deltaic marine and open-shelf assemblages.

Reophax nana Rhumbler (Pl. 1, Fig. 2); 1911, Plankton-Exped. Humboldt-Stiftung, Ergeb., Bd. 3, L.c., p. 182, Pl. 8, Figs. 6–12. Principally in sound environment and in zone of mixing between sound and deltaic marine environments.

Reussella atlantica Cushman (Pl. 3, Fig. 9); *Reussella spinulosa* (Reuss) var. *atlantica*, 1947, Contr. Cushman Lab. Foram. Res., Vol. 23, Pt. 4, p. 91, Pl. 20, Figs. 6, 7. Very rare occurrences in open-shelf environment.

Streblus beccarii (Linne) variants (Pl. 3, Figs. 10, 13); *Nautilus beccarii*, 1758, Syst. Nat., Ed. 10, p. 710. One of most abundant and widely distributed species in area studied. Not found in marsh environment and occurs only in low frequencies in deltaic marine fauna; relatively abundant in all other environments.

Textularia earlandi Parker (Pl. 1, Fig. 10); 1952, Bull. Mus. Comp. Zool., Vol. 106, No. 10, p. 458 (footnote). With one exception, this species has been found only in deltaic marine environment. Rare specimens in marsh samples have been referred to *T. earlandi* but are much smaller and have more fragile test than the marine forms.

Textularia mayori Cushman (Pl. 1, Figs. 11a, b); 1922, Publ. 311, Carnegie Inst. Washington, Vol. 17, p. 23, Pl. 2, Fig. 3. Typical of open-shelf environment; relatively small specimens found in low frequencies in zone of mixing between open-shelf and deltaic marine assemblages.

Triloculina sidebottomi (Martinotti) (Pl. 1, Figs. 11a, b); *Sigmoilina sidebottomi*, 1920, Atti. Soc. Ital. Nat., Vol. 59, Pl. 2, Fig. 29, Text Figs. 59–61. Most abundant in sound fauna and occurs in significant quantities in fluvial marine, deltaic marine, and open-shelf faunal associations.

Trochammina inflata (Montagu); *Nautilus inflatus*, 1808, Test. Brit., p. 81, Pl. 18, Fig. 3, Marsh species and not found in any other environment.

Trochammina lobata Cushman (Pl. 1, Figs. 19a–c); 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 18, Pl. 2, Fig. 10. In low frequencies in sound and open-shelf assemblages.

Uvigerina parvula Cushman (Pl. 3, Fig. 12); *Uvigerina peregrina* Cushman var. *parvula*, 1923, Bull. U. S. Nat. Mus., Vol. 104, Pt. 4, Pl. 42, Fig. 11. Characteristic of open-shelf fauna and has been found in deep-water deltaic marine fauna.

Virgulina complanata Egger (Pl. 3, Fig. 1); *Virgulina schreibersiana* Czjzek var. *complanata*, 1893, Abhandl. k. bay. Akad. Wiss. München, Vol. 18, Pt. 2, p. 292, Pl. 8, Figs. 91, 92. In very low frequencies in deep-water deltaic marine and open-shelf faunas.

Virgulina pontoni Cushman (Pl. 2, Fig. 17); 1932, Contr. Cushman Lab. Foram. Res., Vol. 8, Pt. 1, p. 17, Pl. 3, Fig. 7. In the deltaic marine assemblage and also reported by others from open-shelf environment.

Virgulina sp. (Pl. 3, Fig. 2). This very small species occurs principally in deltaic marine environment and where this environment mixes with that of the sound.

Virgulina (*Virgulinella*) *pertusa* Reuss. Cushman (Pl. 3, Fig. 3); 1937, Spec. Publ. 9, Contr. Cushman Lab. Foram. Res., p. 31, Pl. 5, Figs. 6–9. Until recently, subgenus *Virgulinella* was thought to have been extinct since Pliocene. Species recorded from Recent sediments of Venezuela and Peru by Todd and Bronnimann (1957, p. 33); Boltovskoy (1957, p. 50) reports another species and subspecies of *Virgulinella* from Recent off Argentina. Possibility remained that these reported specimens were reworked and that subgenus was in fact extinct. However, most specimens of *V.* (*V.*) *pertusa* found in deltaic marine fauna off eastern Mississippi Delta were stained by rose Bengal and are assumed to have been living at time of collection.

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SEDIMENTARY FACIES FROM SHALLOW BORINGS IN LOWER MISSISSIPPI DELTA[1]

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ABSTRACT

Detailed analyses of the marginal sediments of the Mississippi Delta have permitted the development of criteria for recognizing deltaic environments. In order to test the use of these criteria as a means of improving the interpretation of older sediments, six borings were jetted into the lower delta to depths up to 45 feet and the continuous samples along these borings were given intense study. The Foraminifera, the constituents of the coarse fractions, the grain-size parameters, and the sedimentary structures served to diagnose the environments in which most of the sediments were deposited.

A boring into the end of Baptiste Collette subdelta showed at least three alternations between sound and deltaic deposits. A boring into outer Main Pass, where the water was 26 feet deep in 1860, showed the advance of the delta over the sound facies. The boring into the end of North Pass is interpreted as showing the muddy fill of an abandoned pass overlying a laminated river-mouth bar, which in turn overlies a probable barrier-island deposit. The other borings into the birdfoot delta pass through deposits characteristic of interdistributary bays and of the platforms bordering the delta margin, but do not reach the clayey foreset beds beyond the delta margin.

The borings cast doubt on the concept of bar-finger "sands" forming in front of the advancing deltaic lobes in the birdfoot delta. The sediments encountered were no sandier than those off the present mouths which consist predominantly of silt and clay. The only place where a clean sand was penetrated which could be compared with the thick sand sections shown in lower delta borings by the U. S. Engineers yielded sediment differing from that of the present-day river-mouth bars. More borings with detailed studies of the core samples are needed before accepting or rejecting the bar-finger "sand" interpretation.

INTRODUCTION

Sedimentary facies of delta deposition were established as one of the results of the analysis of the large collection of A.P.I. Project 51 samples obtained from the margins of the east Mississippi Delta (Shepard, 1956). The deposits were divided into topset beds, which include river channel, natural levee, marsh, interdistributary bay, and delta-front platform; foreset beds; and bottomset beds. Facies that are less directly related to the delta include inlet deposits in the entrance to Chandeleur and Breton sounds, open-sound deposits inside the islands, and reworked Mississippi Delta deposits, the last occurring in part as barrier-island sands. To the east these delta facies overlap onto east Gulf shelf sediments which have a different mineral assemblage from that carried by the present river.

The study of surface sediment samples within the delta area by Phleger (1955) and Lankford (1959) has established six foraminiferal environments. Assemblages including marsh, interdistributary bay, and fluvial marine (river channels, near their mouths) are associated with the topset beds of the delta. The foreset and bottomset beds usually contain the deltaic marine fauna, although commonly a sparse sound assemblage occurs in the shoaler parts of the foreset beds and appears to result from intermediate salinity waters lying above

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[1] Contribution from the Scripps Institution of Oceanography, New Series. This investigation was supported by a grant from the American Petroleum Institute, Project 51. Manuscript received, April 30, 1958; revised, June 15, 1959.

[2] University of California, Scripps Institution of Oceanography, La Jolla, California.

Contributions from the Scripps Institution of Oceanography, New Series, 1101

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the more saline Gulf waters. A more abundant sound fauna is typical of bays and lagoons of low salinity which are not necessarily related to delta formation. The open-shelf environment is characterized by a normal marine assemblage and shows little if any delta influence.

The application of these facies to the interpretation of older delta deposits was tested by study of six borings which were obtained from the natural levees by using a water-jet boring device designed by J. R. Curray and G. A. Rusnak which made it possible to take practically continuous cores down to a maximum depth of 45 feet.

It was not everywhere possible to recognize the exact facies of these samples taken at depth, but in general the relation of deposits to the growing delta at the time of deposition could be ascertained. Grain-size analyses, composition of the coarse fraction, and sedimentary structures all proved useful but the most helpful information concerning depositional environments has come from the study of the Foraminifera, reported by Lankford as a part of the present paper. In some places macro-organisms were available and these were identified by R. H. Parker, who had previously studied the assemblages in association with the delta margin (Parker, 1956).

The information from the borings to be described is not in any way comparable quantitatively with the vast amount of material which has been used by Fisk and others (Fisk, 1944, 1952; Fisk *et al.* 1954; and Fisk and McFarlan, 1955) to interpret the Quaternary history of the entire delta. More specific interpretations of this new material, however, are felt to be possible because our investigations have included detailed studies of the individual samples, using size analyses, coarse-fraction techniques, and extensive study of the Foraminifera. No such detailed studies were made in the broader coverage by Fisk and his associates, who based their interpretations on examination of the logs from numerous borings with only a few analyses of the sediment or of the organisms. Thus the results reported by the present paper which are paleontologic and petrographic differ considerably from those of Fisk and his collaborators which were stratigraphic.

PREVIOUS STUDY AND INTERPRETATION OF MODERN DELTA FRAMEWORK

Fisk and his collaborators (1954) have developed a very appealing interpretation of the general framework of the modern Mississippi Delta with its "bird-foot" pattern (Fig. 1A). They think of the distributary lobes as bar fingers of "sand"[3] which built forward onto the Gulf bottom with the "sand" having a base at about 200 feet. Above the "sand" is a thin cover of muddy natural levee deposits with "an average maximum thickness of 20 feet" (Fig. 1B). The "sand" is thought to have formed on the bar at the mouths of the estuaries, building forward on the pro-delta slope down to about 100 feet in depth. The 200-foot depth

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[3] In most publications Fisk has "sand" in quotations. Presumably the quotation marks refer to the sand containing variable amounts of fine sediment.

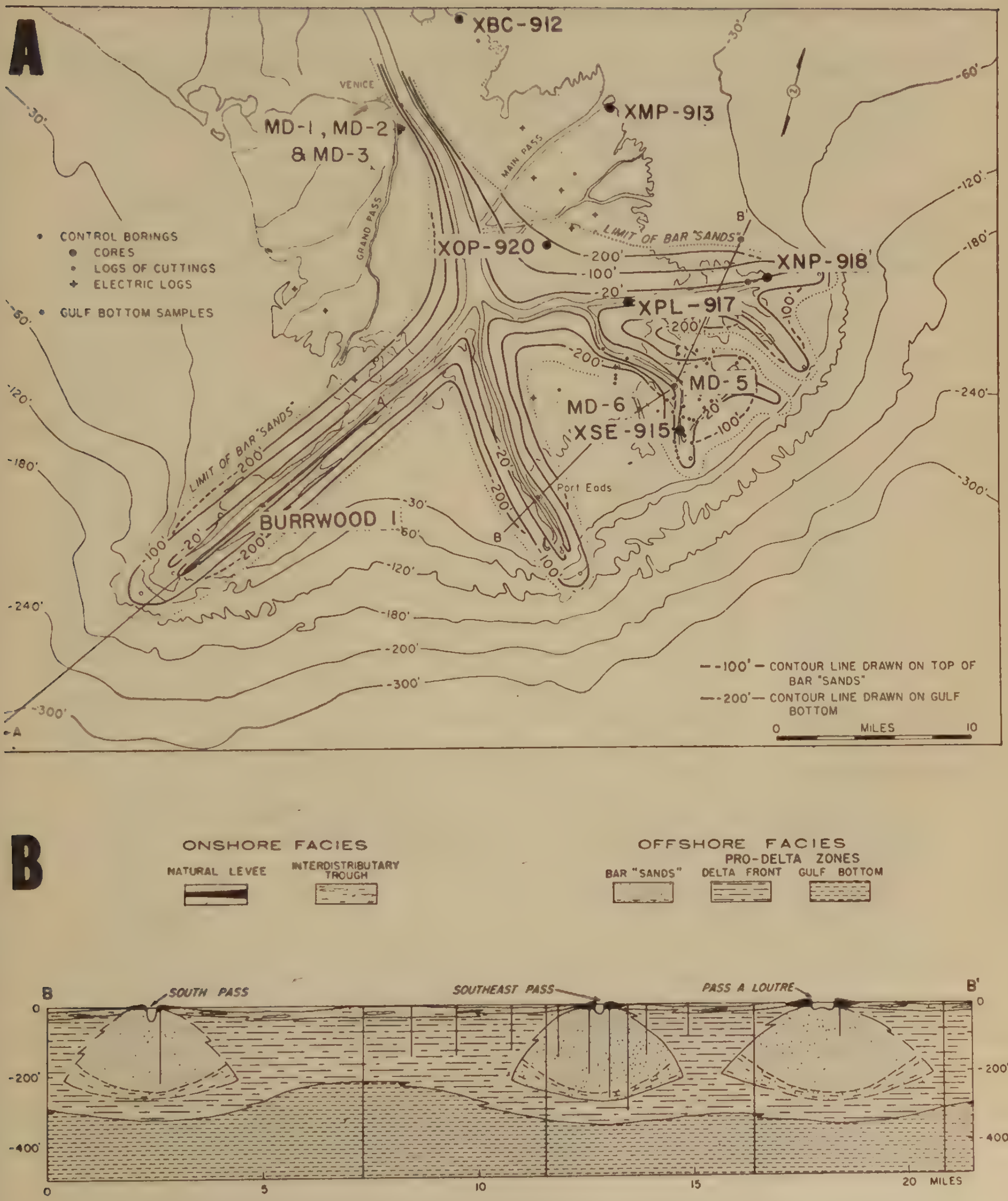
A
XBC-912
VENICE
MD-1, MD-2
& MD-3
XMP-913
MAIN PASS
GRAND PASS
LIMIT OF BAR "SANDS"
XOP-920
XNP-918
XPL-917
MD-5
MD-6
XSE-915
Port Eads
BURRWOOD 1
• CONTROL BORINGS
● CORES
• LOGS OF CUTTINGS
✦ ELECTRIC LOGS
• GULF BOTTOM SAMPLES
-30'
-60'
-120'
-180'
-240'
-300'
-20'
-100'
-200'
A
B
B'
- -100' — CONTOUR LINE DRAWN ON TOP OF BAR "SANDS"
—-200'— CONTOUR LINE DRAWN ON GULF BOTTOM
0 MILES 10
B
ONSHORE FACIES
NATURAL LEVEE
INTERDISTRIBUTARY TROUGH
OFFSHORE FACIES
PRO-DELTA ZONES
BAR "SANDS"
DELTA FRONT
GULF BOTTOM
SOUTH PASS
SOUTHEAST PASS
PASS A LOUTRE
0
-200'
-400'
0
5
10
15
20 MILES

Fig. 1.—Bar "sands" as interpreted by Fisk and McFarlan (1955). Location of U. S. Engineer and Scripps Institution borings are included in A. Location of cross section B is indicated on map. See also Fig. 3.

of the "sand" in the borings is attributed to subsidence, partly by compaction, following deposition. The "sand" fingers are said to be bordered by clayey "interdistributary trough" sediments which were deposited in the bays and marshes between the various distributaries.

The Scripps Institution study of the marginal sediments of the Mississippi Delta (Scruton, 1955, and Shepard, 1956) yielded data which were difficult to reconcile in some respects with this simplified framework. In the first place our samples of the bar slopes indicated that sediment with more than 10 per cent of sand-size material was virtually confined to depths of less than 50 feet and even the upper parts of the slope rarely had more than 25 per cent sand[4] (Fig. 2). Furthermore, the platforms around the river mouths also were found to contain more silt and clay than sand (Shepard, 1956, Figs. 35, 41), so that they should only be considered as "sand" in very restricted localities.

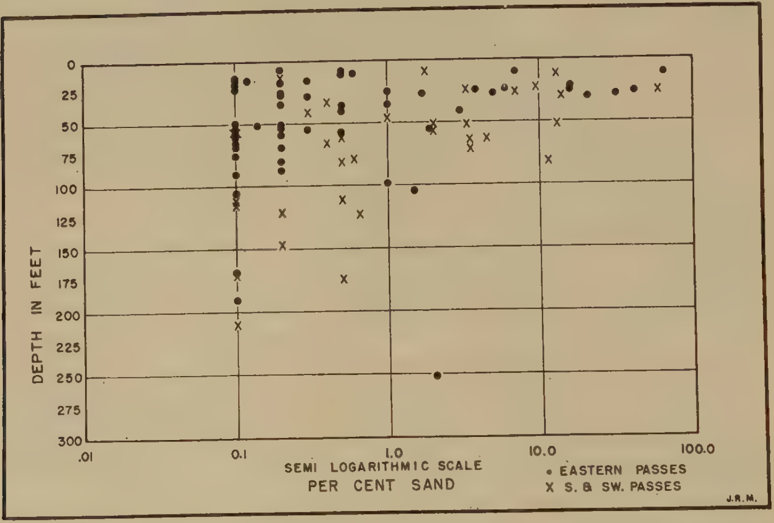

FIG. 2.—Variation in sand content plotted against depth on slopes of eastern and southern passes of Mississippi Delta. Very low percentages of sand are found even in shallow water and nearly all relatively high percentages occur in water less than 25 feet deep.

An examination of the logs of the borings reported by Fisk (1952) were not very helpful. Only six borings are given which penetrate through the zone considered by Fisk to represent bar fingers. These are reproduced in Figure 3 (locations in Fig. 1A) and include three logs of wells in the birdfoot delta and three from the levees of the Venice area 8 miles upstream from Head of Passes. Only a few anal-

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[4] Only six analyses of these slope-samples are reported by Fisk and these agree quite well with our findings.

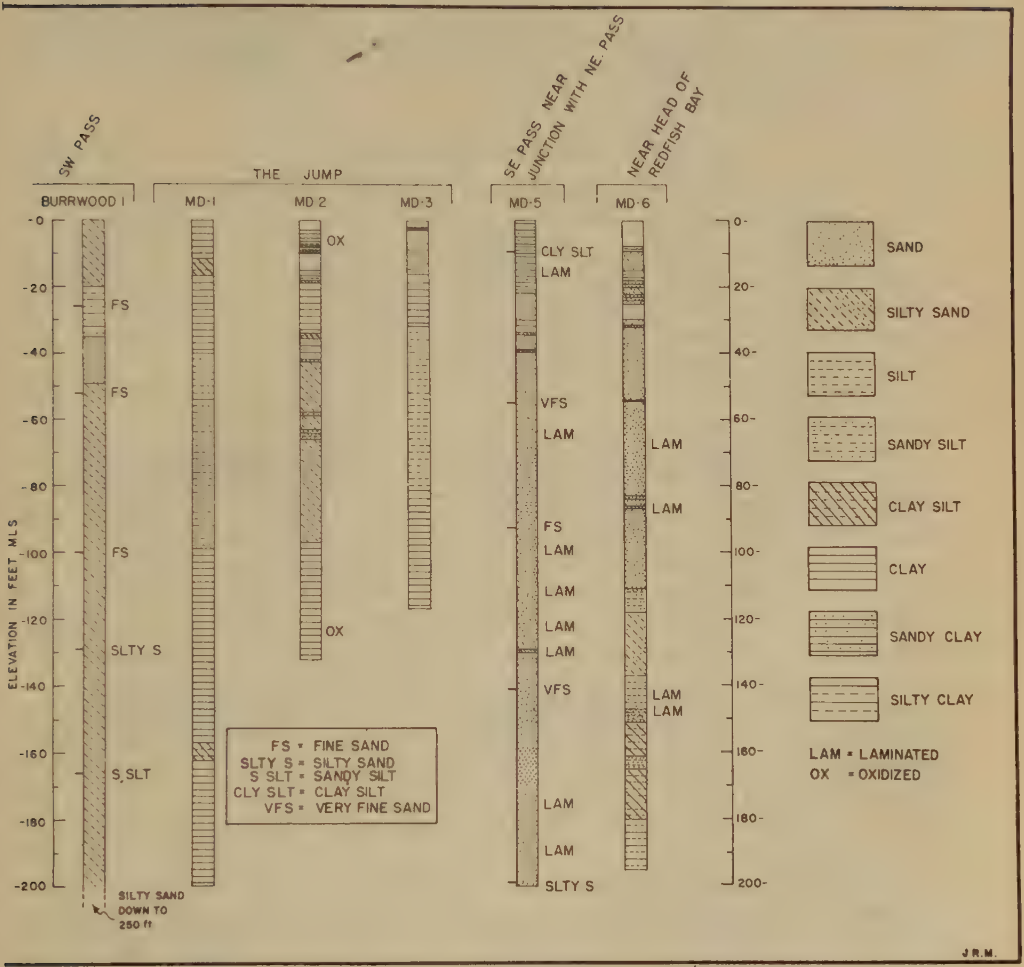
SW PASS
BURRWOOD I
THE JUMP
MD-1
MD 2
MD-3
SE PASS NEAR JUNCTION WITH NE. PASS
MD-5
NEAR HEAD OF REDFISH BAY
MD-6
ELEVATION IN FEET MLS
-0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
FS
FS
FS
SLTY S
S SLT
SILTY SAND DOWN TO 250 ft
OX
OX
CLY SLT
LAM
VFS
LAM
FS
LAM
LAM
LAM
LAM
VFS
LAM
LAM
SLTY S
LAM
LAM
LAM
LAM
0-
20-
40-
60-
80-
100-
120-
140-
160-
180-
200-
FS = FINE SAND
SLTY S = SILTY SAND
S SLT = SANDY SILT
CLY SLT = CLAY SILT
VFS = VERY FINE SAND
SAND
SILTY SAND
SILT
SANDY SILT
CLAY SILT
CLAY
SANDY CLAY
SILTY CLAY
LAM = LAMINATED
OX = OXIDIZED
J.R.M.

FIG. 3.—General lithology of borings in lower Mississippi Delta which should traverse area marked as bar "sands" according to interpretation of Fisk and McFarlan. For locations see Fig. 1A. Logs from Fisk (1952). Sediment types marked on right of well logs are based on samples analyzed by Fisk.

yses have been reported from these borings. The boring logs indicate thick sand or silty sand zones underlying the lower delta although the depths at which these appear are not at all consistent with the depths at which one might expect the muddy sands of the bars, judged from our results (Fig. 2). Since no petrographic or paleontologic study has been made of the "sands" in these borings it is not easy to interpret their origin. Thick sands along the Gulf coast are known to be due to the upgrowth of barrier islands during rising sea-level (Shepard and Moore, 1955, p. 1578); also they might form in the deep river channels as point bars on the inside of bends.[5]

SCRIPPS INSTITUTION BORINGS IN MODERN DELTA

In an attempt to apply the environment criteria from present-day sediments to interpret older formations we put down six shallow holes in the modern delta. Three of these should have penetrated into the supposed "sand" fingers on the natural levees respectively at the mouths of North Pass and Southeast Pass and 5 miles upstream on Pass a Loutre. Three other borings were made by us in the natural levees of other parts of the modern delta including the mouths of Main Pass and Baptiste Collette and 5 miles upstream on Octave Pass (Figs. 1, 6). The borings were continuous and the entire section was photographed (Fig. 5) and studied in detail.

Sand-silt-clay content.—Figure 4 indicates the sand-silt-clay content of the sediments obtained in these jet borings. The analyses are based on the same procedure which we have used in our other Gulf of Mexico samples (Shepard and Moore, 1955, p. 1479), i.e., obtaining the total sand by screening and using hydrometers to determine the silt and clay content. Sodium hexametaphosphate was used for disaggregating the fine fraction. In constructing the sand-silt-clay diagrams, in addition to 89 grain-size analyses, use was made of the log descriptions of the cores. The latter served as a guide for evaluating the descriptions from unanalyzed parts of the core. The depths in the boring at which the analyses were made are shown by tick marks on the left margin of each boring log. In discussing the results of these grain-size analyses use is made of the terminology which was established by obtaining the majority opinion of a group of sedimentationists (Shepard, 1954).

The most significant findings from the plotted results of the sand-silt-clay relations are the following.

1. There are frequent alternations between fine sand (or silt) and silty clay (see also Fig. 5). These alternations are especially marked in the boring in Southeast Pass (XSE-915).
2. Clean sand layers are rare, most sediment having less than 50 per cent sand.
3. Silt is more common than sand and clay, although in the Baptiste Collette (XBC-912) and the Pass a Loutre (XPL-917) borings clay content is somewhat in excess of silt.
4. There is little, if any, consistent trend of the sand-silt-clay content with depth. Sand is generally low near the surface but varies irregularly at depth. Sev-

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[5] The channels of the Mississippi are commonly 50–100 feet deep. Migration by cutting on the outside and deposition on the inside could, therefore, produce thick sand deposits. On the other hand, the filling of an abandoned channel consists ordinarily of fine sediment (Fisk, 1944, p. 20).

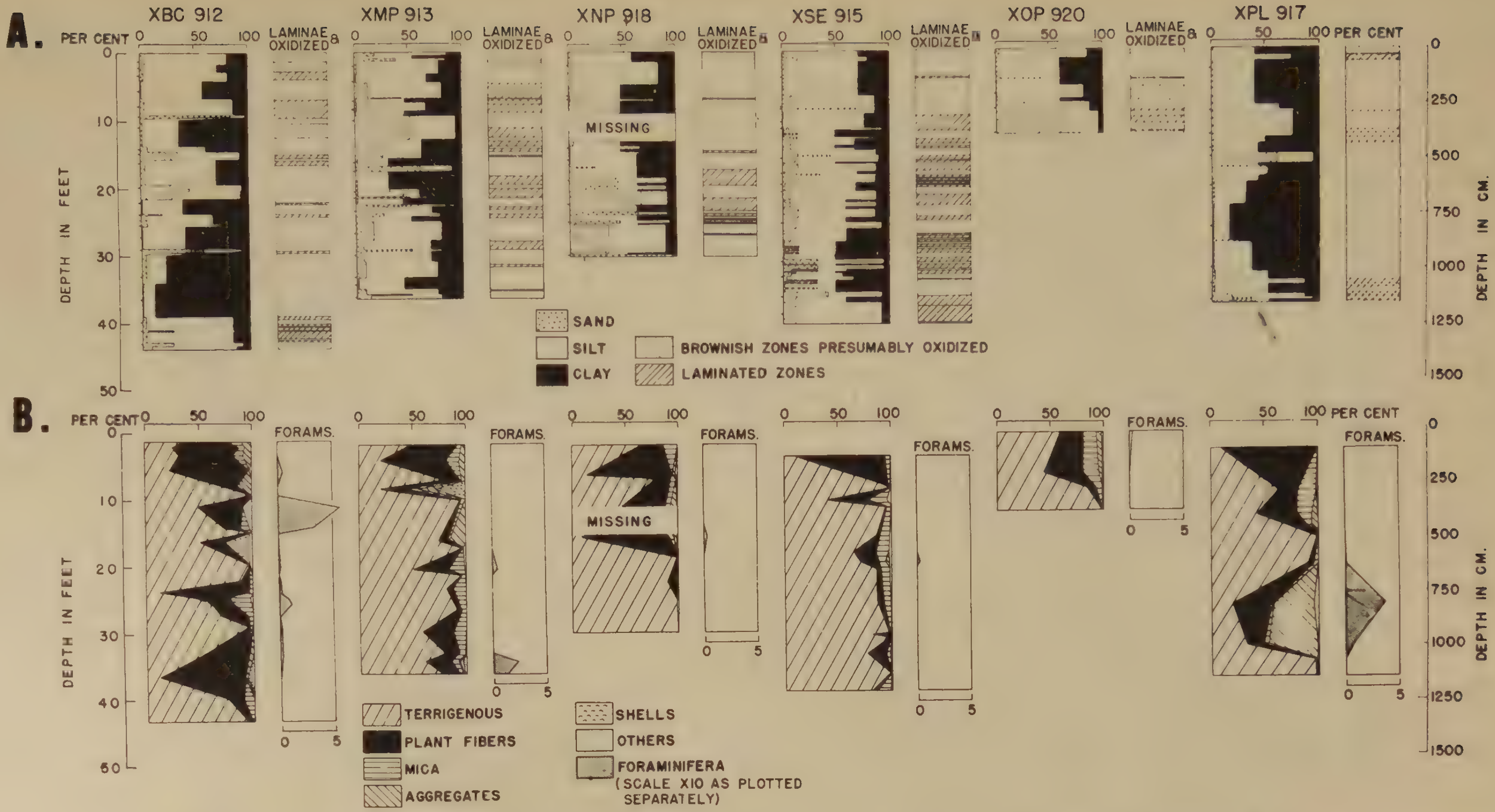

FIG. 4.—Analyses of jet borings in birdfoot delta. Tick marks on side show depth of analyzed samples. See Figs. 1 and 6 for locations. A. Sand-silt-clay percentages, with distribution of laminae and oxidized layers. B. Percentage of principal constituents in coarse fraction. Percentage of Foraminifera given separately at increased scale.

eral of the cores have a fairly high sand content near the 10-foot level, which may be a coincidence.

A sand obtained in the North Pass boring had about 90 per cent sand and only 3 per cent clay. It has the coarsest sand (Md. 2.6ϕ) of any material obtained in our borings from the passes. The result of size analysis of this sand bed was unique among those of the jet borings in having higher weight per cent in the $\frac{1}{4}-\frac{1}{8}$-mm. fraction than in the $\frac{1}{8}-\frac{1}{16}$-mm. Previous studies of the delta (Shepard, 1956, p. 2562) showed that samples with this size distribution do not come from the river-mouth bars but from the longshore bars and barrier beaches found around the periphery of the delta where the waves have sorted the material. This same size relation is found also in Breton Island and in the Chandeleur Islands, both of which represent old reworked delta deposits. It is also common in the river channels upstream from the birdfoot delta (Kolb, 1956), and occurs sparingly in river bars of the lower delta. A possible explanation for the coarser sand from the base of the North Pass boring is that it is a submerged longshore bar or barrier-beach deposit. Alternatively it could represent a point bar deposit in a river channel, perhaps formed prior to the most recent advance.

A comparison with logs from borings made by the Engineers, reported by Fisk (Fig. 3), shows that our jet borings are fairly typical. More samples would be desirable, but in view of our analyses and those reported by Fisk, the use of the term "bar 'sands' " to describe the birdfoot distributary sediments of the Mississippi Delta seems to be rather questionable.

Laminated zones.—The study of the cores showed that their most striking visual characteristic was their many zones with lamination, i.e., layering less than 1 cm. thick (McKee and Weir, 1953). This lamination alternates with relatively massive clayey zones and occasionally with massive silty sands or sandy silts (Figs. 4, 5). None of the borings showed lamination at or near the surface, although this is probably because all of the upper parts of the borings represent either the emerged levee or a zone a foot or more thick that had been built up by some minor engineering operation. In general the lamination begins 5–10 feet below the surface, but these zones are very discontinuous. In two of the longest borings (XBC-912 and XPL-917) lamination appears to be best developed in the upper part and near the bottom, whereas there were fairly extensive zones of massive clay in between. In XNP-918, XSE-915, and XOP-920 lamination occurs only at considerable depth within the borings.

Lamination has been found to be virtually confined to the pro-delta platform and hence to water depths of less than about 10 feet (Shepard, 1956, p. 2602), although a certain amount of stratification, in contrast to lamination, is found at much greater depth.[6] Similarly off the Orinoco Delta, Nota (1958, p. 31) found the laminated sediments confined to the nearshore area. Since the laminated zones within modern sediments around the birdfoot delta are shallow, the laminae in the borings could be interpreted reasonably as very shallow-water deposits. If this interpretation is correct, it would appear that the borings, in spite of extending to depths of as much as 45 feet, penetrate sediments that were probably formed in shoaler water and have since subsided, perhaps, following the suggestion of Russell (1936, p. 45) and Treadwell (1955, p. 40), as the result of sinking of the delta lobes into somewhat more fluid deposits. This sinking would be additional to the normal compaction of sediments within the delta lobe. It is equally possible that the deeper parts of the borings represent topset beds formed during early advances over the platform of the birdfoot delta which were temporarily halted, giving time for subsidence.

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[6] On the other hand, some sea floor cores obtained by J. R. Curray seaward of Trinity Shoal off western Louisiana showed lamination at depths as great as 42 feet, possibly representing an older cycle.

Coarse-fraction studies.—The samples chosen for microscope study were sieved to the standard Wentworth sizes (divided by phi units 0, 1, 2, 3, and 4) and counts were made of the constituents in representative samples from each sieving. The total was then calculated according to the weight of the different sievings. The results of these studies are shown in the plottings (Fig. 4B). The principal constituents found are terrigenous minerals, plant fibers, mica, aggregates, and in a few samples, shells and Foraminifera. Nearly all of the Foraminifera are benthonic.

The most conspicuous feature of the coarse fraction distribution is the very high content of woody material, consisting primarily of plant fibers and secondarily of seed pods. The plants are especially abundant in the coarse fractions near the surface, although in four borings the abundance increases a little directly below the surface.

The plant fibers show an increase in carbonation with depth, judged from the blacker color. Woody material is abundant at various depths in the cores, although in no case was it common at the bottom of the hole, perhaps because the abundance of woody material generally shows an inverse relation to the sand content and the sand content is generally higher at the base. Along with the plant fibers a considerable abundance of mica and aggregates was found, as is also true of the surface sediments obtained around the margins of the Mississippi Delta. It may be significant that the aggregates show little if any change with depth either in their color (generally orange) or in their quantity. Terrigenous minerals generally increase somewhat with depth in the borings. Shells occur irregularly, but in significant quantities only at depths in excess of 8 feet. The same is true of the Foraminifera, which are very sporadic in their abundance.

Small quantities of other constituents were observed. Ostracods were found in a fairly large percentage of the samples, although not with an abundance large enough to be plotted in the diagram. Glauconite was found in a few samples and virtually all of it was the light green, second-cycle glauconite found also in the samples in and around the margin of the delta (Shepard, 1956, p. 2581). Diatoms were found in about a fifth of the samples, although not in abundance. Radiolarians (probably all reworked fossils) were found in a few of the samples. Pyrite occurred in rather appreciable quantity in three samples, all lying between 5 and 10 feet of the surface. It was not observed at other depths. Amber was found in a few samples, occurring as small grains. Each of the samples with amber has an abundance of wood.

Color.—Most of the sediments are gray, or slightly greenish gray, very similar to the near-surface materials. However, there are a few zones that are brownish and appear to be oxidized. It is possible that this oxidation has occurred after the collecting of the samples, although the cores were only stored for 3 weeks and were still wet when opened. Most of the oxidation is found in definite layers which are indicated in Figure 4. In several places the clay had a somewhat pinkish tinge, which did not seem to have any relation to other characteristics and occurred sporadically.

DEPOSITIONAL ENVIRONMENTS AS INDICATED BY FORAMINIFERA AND MACRO-ORGANISMS

All the samples cut from our jet borings have been examined for Foraminifera by Lankford and for macro-organisms, where present, by Robert H. Parker. The material studied in this report had been prepared by soaking in sodium hexametaphosphate and using standard techniques for grain size and coarse-fraction analyses (Shepard and Moore, 1955, p. 1500). Macro-organisms do not appear to be affected by these processes but the arenaceous or agglutinated Foraminifera commonly are destroyed by the deflocculating action of sodium hexametaphosphate. This is particularly true for poorly cemented arenaceous species indigenous to marginal marine environments.[7] Agglutinated Foraminifera occurring in the open-shelf environment are more strongly cemented and most of them survive the deflocculation process. For this reason, the foraminiferal assemblages may not agree in detail with those obtained by workers using other sample preparation procedures.

A relative scarcity of micro-organisms exists in our jet borings. There are two possible explanations of this. First, the sedimentary and faunal environments penetrated are those characteristic of the shallow sound and shallow-water delta platform. Studies of modern Foraminifera in surface sediments of the present delta (Lankford, 1959) and the coarse-fraction studies (Shepard, 1956) show that the microfauna normally constitutes only a small percentage of the delta-platform sediments. A second reason is that arenaceous Foraminifera have been destroyed by the deflocculation process. A few generalizations, however, based on the sparse faunal associations may be made. In the following faunal descriptions, the Foraminifera are grouped into environmental assemblages with depth in the boring; the relative frequencies of species within a stratigraphic unit are indicated by the symbols: A = abundant, C = common, R = rare, VR = very rare.

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[7] Untreated material from relatively long cores and older rocks indicates that these genera and species commonly survive diagenesis. On occasions, even the delicately constructed arenaceous Thecamoebina, a closely related group of non-marine rhizopods, have been found in rock samples.

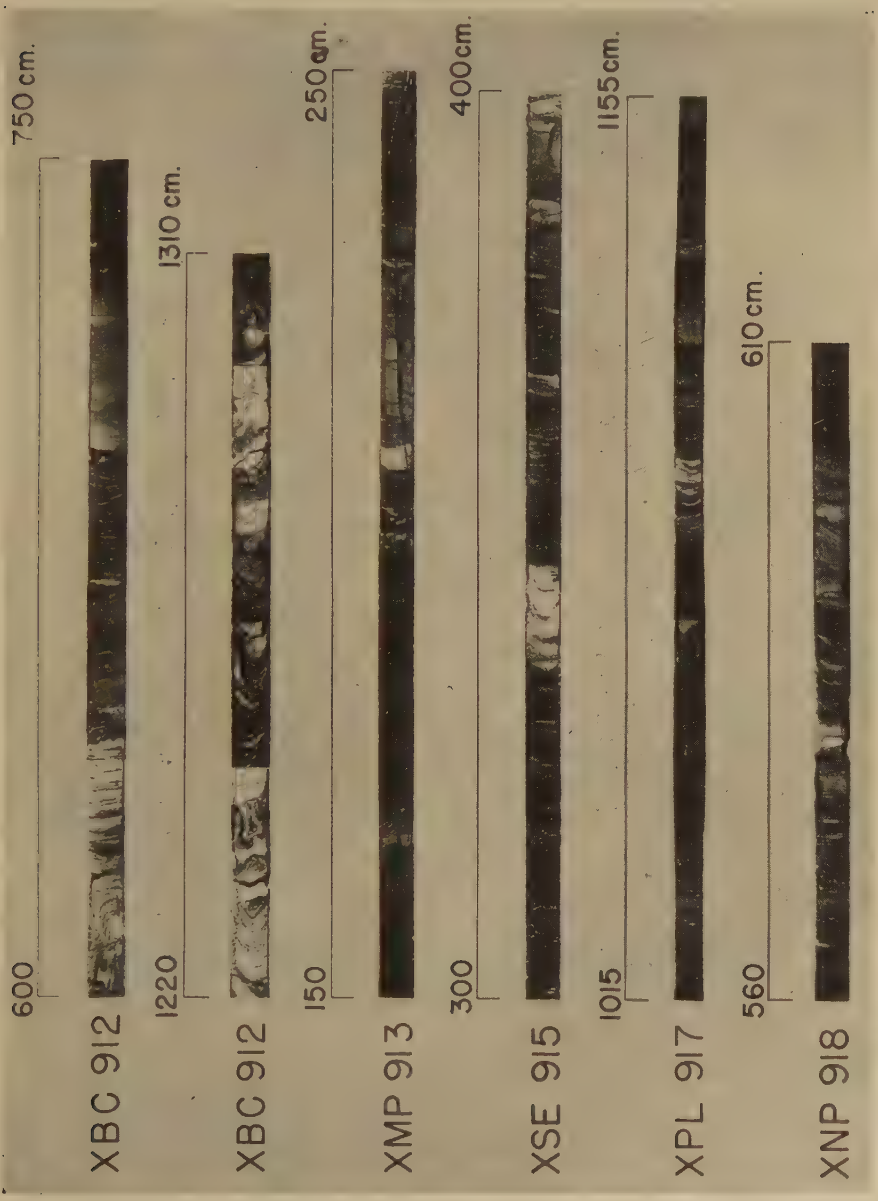
XBC 912
600
750 cm.
XBC 912
1220
1310 cm.
XMP 913
150
250 cm.
XSE 915
300
400 cm.
XPL 917
1015
1155 cm.
XNP 918
560
610 cm.

FIG. 5.—Typical sections from borings made by Scripps Institution. Dark areas indicate mud, and light areas sand or coarse silt. Contortions like those in second photograph are probably due to boring method. Compare Fig. 4 for information concerning sections.

Boring XBC-912.—In the Baptiste Collette subdelta boring, from the surface down to 8 feet, there are marsh deposits with interfingering shallow sound deposits representative of the modern cycle. The interval between 10 and 14 feet is a transition zone either barren or containing sound Foraminifera. A second delta mass is found between 14 and 22 feet, which is underlain by more sound deposits down to about 32 feet. The sequence is repeated a third time, with deltaic organisms found from 32 to 41 feet and probable sound deposits at the bottom of the hole.

BORING XBC-912

Depth in Feet	*0–3*	*5–8*	*10–14*	*14–22*	*23–29*	*32–40*	*41–42*
Environment of Deposition	*Marsh*	*Marsh and Sound*	*Sound*	*Deltaic*	*Sound*	*Deltaic*	*Sound (?)*
Species							
Haplophragmoides manilaensis	A	R					
H. wilberti	R						
Streblus beccarii & vars.		C	A	R	A	VR	R
Elphidium delicatulum		R		VR	VR		
Triloculina sidebottomi		R	VR		R		
Elphidium matagordanum		VR	C	VR	R	VR	
E. gunteri			C	R	A	VR	R
E. poeyanum			C	R	A	VR	
Arenoparrella mexicana			VR				
Nonionella opima					VR		
Elphidium incertum mexicanum					C		
Quinqueloculina lamarckiana					A		
Q. poeyana					R		
Hanzawaia strattoni							VR
Nonionella atlantica							VR

Boring XMP-913.—In contrast to the multiple series described from the Baptiste Collette samples, our boring at Main Pass penetrates only two major sediment sequences. From the surface down to 22 feet, the sediments are deltaic.

BORING XMP-913

Depth in Feet	*0–2*	*6–8*	*10–26*	*26–35*
Environment of Deposition	*Marsh*	*Barren*	*Deltaic*	*Sound*
Species				
Bisaccium imbricatum	VR			
Haplophragmoides manilaensis	C			
Jadammina polystoma	R			
Palmerinella gardenislandensis	VR			
Streblus beccarii & vars.	VR		R	A
Ammotium salsum & vars.			R	VR
Elphidium incertum mexicanum			VR	VR
E. poeyanum			R	C
E. gunteri			R	A
Nonionella opima			VR	R
Triloculina sidebottomi			VR	C
Quinqueloculina lamarckiana				R
Q. poeyana				VR

The foraminiferal assemblages in this section grade downward from marsh to deltaic marine environments. Below 22 feet and to the bottom of the boring, sound deposits are encountered.

Boring XOP-920.—Samples from this short boring at Octave Pass contain very few Foraminifera. Below the marsh material, just beneath the surface, two samples at 6.5 and 9 feet contain sound species. The deepest sample at 11 feet was barren.

Boring XOP-920

Depth in Feet	*0–1*	*4–9*	*11–11.5*
Environment of Deposition	*Marsh*	*Deltaic (?)*	*Barren*
Species			
Haplophragmoides manilaensis	A		
Bisaccium imbricatum	VR		
Elphidium poeyanum		R	
Nonionella opima		VR	
Streblus beccarii & vars.		C	

Boring XNP-918.—Specimens of Foraminifera are relatively rare in this boring. Samples from the surface to approximately 16 feet contain species indicative of the interdistributary bay environment with rare specimens derived probably from adjacent marshes. From 19 feet to the bottom of the boring, the samples are barren of modern Foraminifera.

Boring XNP-918

Depth in Feet	*0–16*	*19–30*
Environment of Deposition	*Interdistributary Bay and Marsh*	*Barren*
Species		
Bisaccium imbricatum	VR	
Elphidium delicatulum	A	
Palmerinella gardenislandensis	VR	
Streblus beccarii & vars.	C	
Trochammina macrescens	R	

Boring XPL-917.—Samples from the upper 16 feet of this boring contain no modern Foraminifera. From 20 feet to total depth of 35 feet, there is a sparse assemblage characteristic of the interdistributary bay environment.

Boring XPL-917

Depth in Feet	*0–16*	*20–35*
Environment of Deposition	*Barren*	*Interdistributary Bay*
Species		
Elphidium delicatulum		C
Streblus beccarii & vars.		C

Boring XSE-915.—The upper 6 feet of this boring contain an interdistributary bay fauna which gives way to barren sands extending from 7 to 12 feet. From 16 to 20 feet, interdistributary bay species are relatively well represented and this fauna again passes into barren sands from 20 to 34 feet. The two bottom samples between 36 and 38 feet, in addition to an interdistributary bay assemblage, contain a well preserved marine fauna indicative of much deeper water. This is interpreted as derived from the erosion of mud-lump islands which commonly occur in the outer parts of the present-day interdistributary bay. This phenomenon has been studied by Andersen (1951) and Lankford (1959).

BORING XSE-915

Depth in Feet	*0–6*	*7–12*	*16–20*	*20–34*	*36–38*
Environment of Deposition	*Interdistributary Bay*	*Barren*	*Interdistributary Bay*	*Barren*	*Interdistributary Bay*
Species					
Ammotium salsum	VR				
Elphidium delicatulum	C		C		R
Streblus beccarii	R		R		R
Nonionella opima			VR		
Elphidium matagordanum			VR		VR
*Bulimina marginata**					VR
*Globigerina bulloides**					R
*Globorotalia menardii**					VR
Rosalina sp.*					VR
Uvigerina parvula *					R

* Mud lump contaminants.

HISTORICAL ASPECTS AND INTERPRETATIONS

Background information that can help with the interpretation of the jet borings comes from the extensive work of the Louisiana geologists, of the Corps of Engineers, and from the Coast and Geodetic Survey charts dating back more than 100 years. The entire birdfoot delta is thought to have developed during the last 450 years (Fisk *et al.*, 1954, p. 98), although other buried delta sequences are found at lower levels in the area.

The fairly complete charts made about 1860 (Fig. 6) provide another check on the age of the fill. In 1860 the site of the Main Pass boring, XMP-913, was in Bay Fondo where a "sound" facies would be expected, and the water was then about 26 feet deep. At least the top 26 feet should represent deltaic deposits consisting of fill from the advancing Main Pass delta during the past century.[8] The interpretation of the Foraminifera shows just such a history. The lower part of the boring is clearly a "sound" facies although woody material suggests some influence of deltaic sedimentation. As the front of Main Pass subaerial delta advanced, the foreset deposits include a deltaic marine fauna which comes in at a point about 20 feet below the present surface.

[8] Compaction or regional subsidence would increase this figure somewhat.

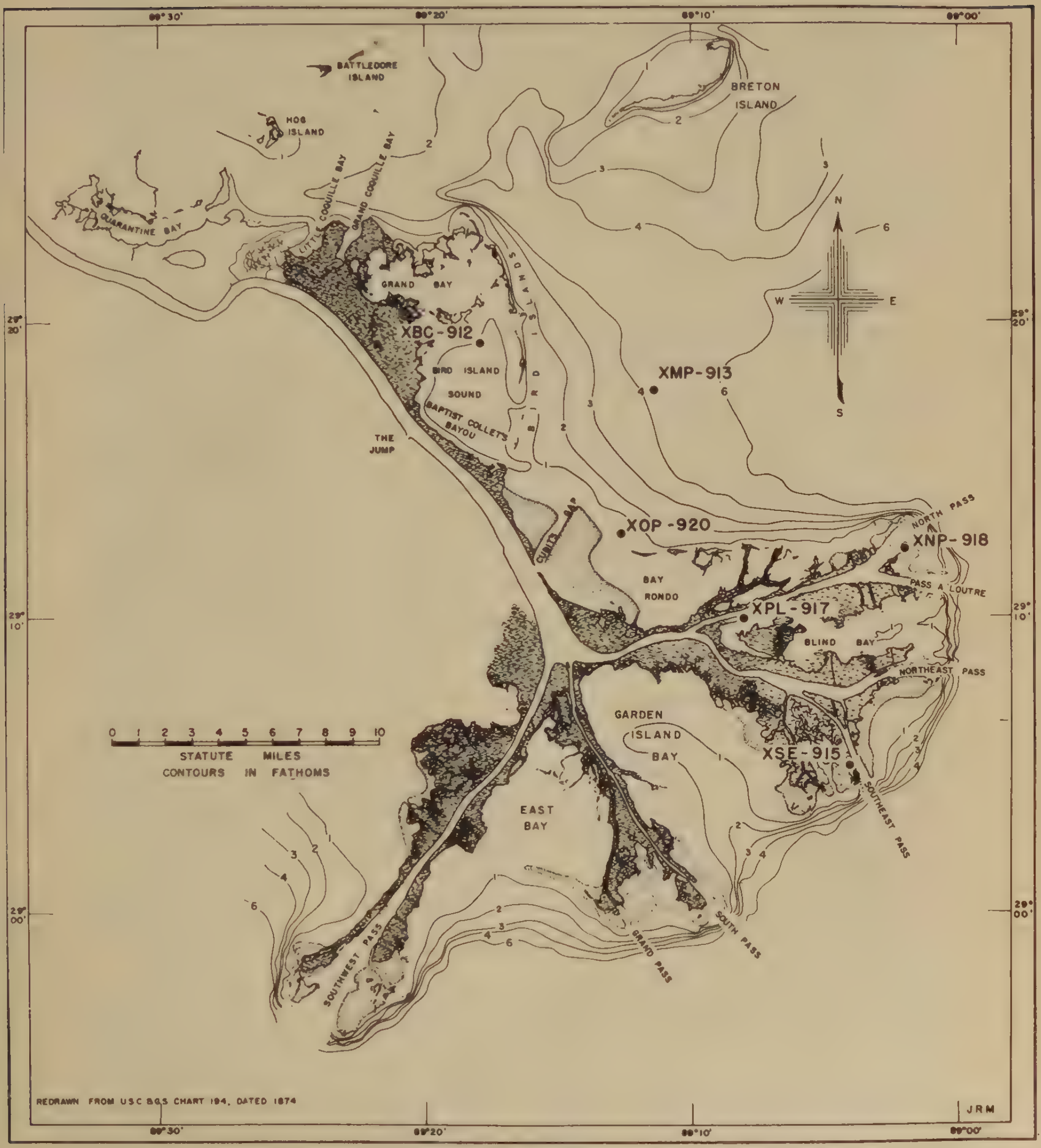
89°30'
89°20'
89°10'
89°00'
29° 20'
29° 10'
29° 00'
BATTLEDORE ISLAND
HOG ISLAND
BRETON ISLAND
QUARANTINE BAY
LITTLE COQUILLE BAY
GRAND COQUILLE BAY
GRAND BAY
BIRD ISLANDS
XBC-912
BIRD ISLAND SOUND
BAPTIST COLLETS BAYOU
THE JUMP
XMP-913
N
S
W
E
CUBITS GAP
XOP-920
NORTH PASS
XNP-918
PASS A LOUTRE
BAY RONDO
XPL-917
BLIND BAY
NORTHEAST PASS
GARDEN ISLAND BAY
XSE-915
SOUTHEAST PASS
EAST BAY
SOUTH PASS
GRAND PASS
SOUTHWEST PASS
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES
CONTOURS IN FATHOMS
1
2
3
4
6
REDRAWN FROM U.S.C.&G.S. CHART 194, DATED 1874
JRM

FIG. 6.—Chart of Delta made in 1860 (published 1874) shows depth of water in fathoms in 1860 at sites of jet borings.

A hundred years ago at the site of the Baptiste Collette boring XBC-912 a shallow sound existed in which the water was about 6 feet deep. At that time there appears to have been some deposition from the Mississippi River through the Baptiste Collette cut. The sediments in the upper part of the boring show about 8 feet of deposits with deltaic aspects, which is only slightly more than the 6-foot depths of the old chart, the difference probably being due to subsidence or sounding inaccuracies. Below the recent delta deposits there are about 6 feet of sediments with a "sound" facies such as would have been expected in the area previous to the artificial cut.

Beneath the shallow sound deposits in XBC-912 an older delta is penetrated. Examination of the 1860 survey (Fig. 6) shows what appears to be an abandoned, partly submerged subdelta east of the Mississippi River extending southeast from Little Coquille Bay to a point approximately 4 miles upstream from Cubits Gap and eastward as far as the Bird Islands. These islands are interpreted as sand barriers derived from the reworking of this second deltaic lobe. The Bird Islands then would be analogous to the Chandeleur chain which is the result of reworking of submerged parts of the abandoned St. Bernard subdelta. Beneath this is still a third delta. These relatively thin deltaic cycles may represent repeated crevassing of the Mississippi levees rather than major delta formation.

At North Pass the 1860 survey shows that what is now the north levee was then a shoal representing the submerged continuation of the south levee. This could mean that the pass migrated southward so that at least the upper part of the boring XNP-918 would represent channel filling. The very low sand content in the boring at North Pass down to 18 feet does not necessarily preclude this possibility because an abandoned channel becomes a settling basin for fine sediment. The underlying part with a higher sand content, beginning at 18 feet, suggests that deposition may have taken place on a platform (bar) at the mouth of the river. Since this is deeper below sea-level than the present-day platforms it seems probable that there has been slight subsidence at this point. Subsidence is also strongly indicated in the Southeast Pass boring XSE-915 where the faunas have an interdistributary bay assemblage at all depths to the bottom of the hole at 40 feet. The Pass a Loutre boring XPL-917 also has the interdistributary bay faunas at least before 20 feet and no indication of sediments deposited beyond the delta platform.

From the results from our analyses of the modern delta borings along with the engineer logs reported by Fisk (Fig. 3), it seems somewhat doubtful that there is a bar finger of "sand" underlying the superficial cover of natural levee deposits. The sand bodies found in the Engineer borings at a variety of depths and with thicknesses up to 200 feet differ in their apparent uniformity from platform deposits around the present river mouths, and, judged from present-day bars, extend through far too long a column to be explained in that way even with some settling. It seems more likely to us that the borings have penetrated through stream-channel deposits, partly point bars, along with some barrier-island sands.

(600)

The distinct possibility exists that the birdfoot delta has built forward on a somewhat older platform and that part of the sands are related to this older generation of stream and barrier deposits. Before the origin of the extensive sands can be ascertained, sediment samples from these depths must be studied in detail.

REFERENCES

Andersen, H. V., 1951, "Report on the Mudlumps at the Mouths of the Mississippi River: Part II, Foraminiferal Faunules from the Mudlumps and Environments in the Vicinity of the Mouths of the Mississippi River," unpublished report, *New Orleans District, Corps of Engineers.* 214 pp.

Fisk, H. N., 1944, "Geological Investigation of the Alluvial Valley of the Lower Misissippi River," *Mississippi River Commission.* 78 pp.

———, 1952, "Geological Investigation of the Atchafalaya Basin and the Problem of Mississippi River Diversion," *ibid.*

———, McFarlan, E., Jr., Kolb, C. R., and Wilbert, L. J., Jr., 1954, "Sedimentary Framework of the Modern Mississippi Delta," *Jour. Sed. Petrology*, Vol. 24, No. 2, pp. 76–99.

Fisk, H. N., and McFarlan, E., Jr., 1955, "Late Quaternary Deltaic Deposits of the Mississippi River," from "The Crust of the Earth," *Geol. Soc. America Spec. Paper 62*, pp. 279–302.

Kolb, C. R., 1956, "Review of Petrographic Studies of Bed Material, Mississippi River, Its Tributaries, and Offshore Areas of Deposition," *Tech. Rept. 3-436, U. S. Army Engineer Waterways Expt. Sta.*, Corps of Engineers, Vicksburg, Mississippi. 37 pp.

Lankford, R. R., 1959, "Distribution and Eocology of Foraminifera from East Mississippi Delta Margin," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 43, No. 9, pp. 2068–99.

McKee, E. D., and Weir, G. W., 1953, "Terminology for Stratification and Cross-Stratification in Sedimentary Rocks," *Bull. Geol. Soc. America*, Vol. 64, No. 4, pp. 381–89.

Nota, D. J. G., 1958, "Sediments of the Western Guiana Shelf," *Report on the Orinoco Shelf Expedition*, Vol. II. 98 pp. H. Veenman and Zorren, Wageningen, Holland.

Parker, R. H., 1956, "Macro-Invertebrate Assemblages as Indicators of Sedimentary Environments in East Mississippi Delta Region," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 40, No. 2, pp. 295–376.

Phleger, F. B, 1955, "Ecology of Foraminifera in Southeastern Mississippi Delta Area," *ibid.*, Vol. 39, No. 5, pp. 712–52.

Russell, R. J., 1936, "Physiography of Lower Mississippi River Delta," *Louisiana Geol. Survey Bull. 8* (Lower Mississippi River Delta), pp. 3–199.

Scruton, P. C., 1955, "Sediments of the Eastern Mississippi Delta," in "Finding Ancient Shorelines," *Soc. Econ. Paleon. and Min. Spec. Pub. 3*, pp. 21–50.

Shepard, F. P., 1954, "Nomenclature Based on Sand-Silt-Clay Ratios," *Jour. Sed. Petrology*, Vol. 24, No. 3, pp. 151–58.

———, 1956, "Marginal Sediments of Mississippi Delta," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 40, No. 11, pp. 2537–2623.

———, and Moore, D. G., 1955, "Central Texas Coast Sedimentation: Characteristics of Sedimentary Environment, Recent History, and Diagenesis," *ibid.*, Vol. 39, No. 8, pp. 1463–1593.

Treadwell, R. C., 1955, "Trafficability and Navigability of Delta-Type Coasts, Trafficability and Navigability of Louisiana Coastal Marshes: Sedimentology and Ecology of Southeast Coastal Louisiana," *Louisiana State Univ. Tech. Rept. 6.* 78 pp.

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Kinetics of Bacterial Growth: Relationship between Population Density and Specific Growth Rate of Continuous Cultures

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SUMMARY: Results from studies of continuous cultures of *Aerobacter aerogenes* growing in chemically defined media indicate that specific growth rate (R) is a function of population density (P) as well as the concentration of the limiting nutrient (S). From these observations, and those of others, the following model for bacterial growth is derived:

$$R = \frac{u_m S}{BP + S},$$

where u_m and B are growth parameters that are constants under defined conditions. This model is believed to have general applicability and to account for bacterial growth in both batch and continuous cultures.

Although biologists have long recognized that the specific growth rate of an organism is often a function of its population density (Pearl & Parker, 1922; Greenleaf, 1926), most bacteriologists are of the opinion that the specific growth rate of a population of bacteria is, ideally, independent of population density. This idea has come down into recent treatments of bacterial growth kinetics of both batch and continuous cultures; and most workers have regarded the specific growth rate of a population growing under conditions of nutrient limitation as a function only of the concentration of the limiting nutrient (Monod, 1942, 1950; Novick & Szilard, 1950; Spicer, 1955; Herbert, Elsworth & Telling, 1956; Moser, 1958). Nevertheless, evidence supporting the contention that specific growth rates of bacterial populations are also functions of population density may be found in the old theories and concepts of 'cell space' (Bail, 1929). Contois (1957) presented evidence to this effect from studies of batch cultures growing under conditions of nutrient limitation. This paper is a report upon further studies undertaken to ascertain the effect of population density upon specific growth rates of bacterial populations, and as a further attempt to derive a more satisfactory model for bacterial growth.

METHODS

Organism. A strain of *Aerobacter aerogenes* was used which grew well in mineral salts media containing ammonium as a nitrogen source and glucose or succinate as a carbon source. In each batch of medium, either the nitrogen source or the carbon source was limiting, all other components being present in excess.

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Culture media. These were compounded from the following stock aqueous solutions:

Solution A, glucose 200 mM.

Solution B, succinic acid 200 mM.; neutralized to pH 6·8 with KOH.

Solution C. $NH_4H_2PO_4$ 250 mM.; $(NH_4)_2HPO_4$ 250 mM.

Solution D. $MgSO_4.7H_2O$ 80 mM.; $FeSO_4.7H_2O$ 3·5 mM.; $MnCl_2.4H_2O$ 5·0 mM.; HCl 1·0 mM.

Solution E. Na_2HPO_4 250 mM.; KH_2PO_4 250 mM.

Solution F. Tetrasodium salt of ethylenediaminetetraacetic acid 25 mM.

All media contained 10 ml. solution D and 5·0 ml. solution F/1. The volumes of solutions C and A or B were changed from time to time to give desired concentrations of ammonium and the selected carbon source. Once the volume of solution C was determined for a given batch or medium, a volume of solution E was added that was sufficient to give a final total phosphate concentration of M/30.

Media were sterilized by passage through sterile molecular filters (Millipore type PH, available from Millipore Filter Corp., Watertown 72, Massachusetts, U.S.A.) and dispensed by the usual aseptic techniques. Before inoculation, the pH value of all media was 6·8.

Method of cultivation. A continuous culture device similar in theory and design to the one developed by Novick & Szilard (1950) was used. The flow rate was adjusted by means of a stopcock which controlled the rate at which fresh medium dripped into the culture vessel. Flow rates were estimated by measuring the volumes of effluent accumulating over known time intervals as well as by drop counts of the inflowing medium.

Culture volume was constant for any given culture, but was different from time to time depending upon the particular culture vessel used. All culture volumes were between 30 and 45 ml.

Mixing and aeration of cultures was accomplished by vigorous sparging with sterile air at a rate of *c.* 1·0 l. air/ml. culture volume/hr.; and the culture device was designed so that the inflowing medium was blown into the culture by the stream of sterile air. In addition, two sterile buoyant rubber disks *c.* 8 mm. in diameter were placed in each culture vessel. By their continuous rapid movement throughout the culture, they scrubbed the walls of the culture vessel and eliminated wall-growth completely. They were also self-cleansing.

Measurement of population density. Population density was measured in units of optical density by a Beckman model DU spectrophotometer (available from Beckman Instruments, Inc., Fullerton, California, U.S.A.) with 1·0 cm. Pyrex cuvettes and at 420 $m\mu$. Comparisons of optical densities with direct counts showed that an optical density of 1·0 corresponded to a direct count of *c.* 5×10^8 organisms/ml. Experience showed that optical density was a linear function of population density within values of optical density of 0·0–0·6. In practice, a sample of a culture was removed aseptically from the culture vessel and diluted until its optical density was less than 0·4 unit. The resultant reading was multiplied by the dilution factor to give the correct population density in units of optical density.

Estimation of concentration of limiting nutrient. Previous experience (Contois, 1957) had shown that with this organism and these media the uptake of the limiting nutrient was a linear function of the increase in population density, or

$$c(S_0-S) = (P-P_0), \tag{1}$$

where S_0 is the initial concentration of the limiting nutrient, P_0 is the initial population density, and c is a yield coefficient. Studies by Dagley & Hinshelwood (1938), Lodge & Hinshelwood (1939), Monod (1942), Herbert *et al.* (1956) and Lawrence (1957) have shown that this relationship is valid under appropriate conditions with various limiting nutrients serving as either carbon, nitrogen, phosphorus, or sulphur sources.

In continuous cultures, S_0 is the concentration of the limiting nutrient in the inflowing medium. Since P_0 is usually insignificant and is washed out of the culture in time anyway (see Spicer, 1955) equation (1) reduces to

$$cS = (cS_0-P), \tag{2}$$

where cS_0 is equivalent to the maximum population density that an organism can attain in a particular medium.

In this study, estimates of the concentration of the limiting nutrient (S) were calculated by equation (2) from measurements of population density (P), the maximum attainable population density (cS_0), and the known values of S_0. In some of the cultures in which the nitrogen source was limiting, its concentration also was measured directly. This was done by removing a sample from the culture vessel and diluting it 1/10 with distilled water. The mixture was filtered immediately through a molecular filter (Millipore type PH) and a sample of the filtrate diluted and nesslerized. After sufficient time, colour development was measured by a Beckman DU spectrophotometer in 10 cm. Pyrex cuvettes at 476 mμ. Estimates of the concentration of ammonium were obtained by comparison with standards.

Estimation of specific growth rates. Monod (1950) and Novick & Szilard (1950) showed that in continuous cultures the change in population density in time is equal to the rate at which the population grows minus the rate at which it is washed out of the culture vessel, or

$$\frac{dP}{dt} = RP-DP, \tag{3}$$

where R is the specific growth rate and D, dilution rate, is defined as the rate of flow of medium through the culture vessel per unit volume of culture (see Herbert *et al.* 1956).

In these experiments, it was desired to obtain estimates of specific growth rate and concentration of limiting nutrient when cultures were at equilibrium. Under such conditions, dP/dt of equation (3) is zero and R is equal to D. Estimates (in units of hr.^{-1}) of specific growth rate, then, were made from measurements of flow rate and the known culture volumes. Replicate estimates were found to have a standard error of *c.* 2 % of the mean of the estimates.

Other observations. Periodic measurements of the pH value of cultures were also made as an aid to assuring that any drastic changes in environmental conditions would be observed. In addition, samples of cultures were examined from time to time during each experiment for the purity of the bacterial species being grown. This was done by microscopic examinations of stained preparations and by plating samples into differential media.

RESULTS

After sterilization, the apparatus was assembled, connected to a reservoir of sterile medium, and placed in an incubator at 27°. The culture vessel was filled with medium and inoculated from a stock culture of *Aerobacter aerogenes*. After growth had proceeded for several hours, fresh medium was allowed to flow through the culture vessel at a constant rate. Determinations of dilution rate (*D*) and population density were made periodically. After a time, the population density reached a constant value, indicating that equilibrium had been established. After several determinations of the equilibrium population density (P_e), the flow rate was adjusted to a new constant value and P_e was again determined. Two typical series of such measurements are shown in Fig. 1. By these methods, values of *R* and their corresponding values of P_e were obtained for each culture (cf. Herbert *et al.* 1956).

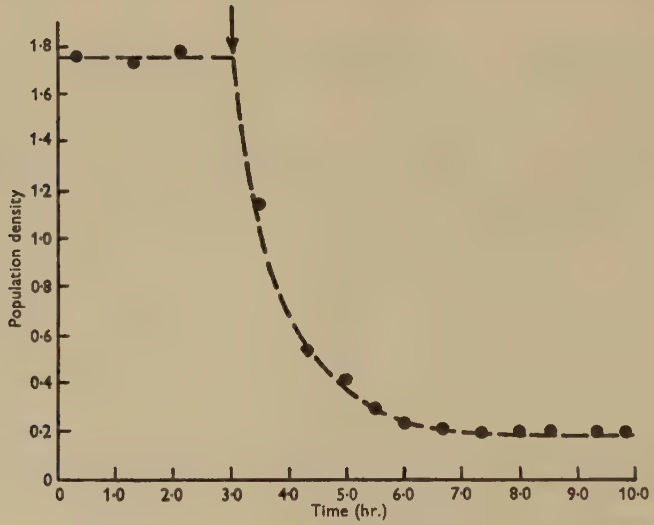

Fig. 1. Change in population density with change in dilution rate of a continuous culture of *Aerobacter aerogenes* with glucose limiting. Dilution rate changed from 0·50 to 1·05 hr.$^{-1}$ at point indicated by arrow after culture had been in equilibrium for *c.* 17 hr.

Estimates of cS_0 were obtained by stopping the flow of medium and allowing the culture to attain its maximum population density at various times during each experiment.

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Table 1. *Relationship between specific growth rate* (R), *population density* (P_e), *and concentration of limiting nutrient* (S_e) *in continuous cultures of* Aerobacter aerogenes *at equilibrium**

R	P_e	$(cS_0 - P_e)$†	S_e‡
Culture 1 A. Glucose as the carbon source and ammonium as the nitrogen source. Glucose limiting at a concentration of 5·55 mM. in the inflowing medium.			
1·07	0·49	2·03	4·48
0·97	1·83	0·69	1·53
0·74	2·20	0·32	0·71
0·49	2·37	0·15	0·34
0·46	2·40	0·12	0·25
0·00	2·52	0·00	0·00
Culture 1 B. Glucose as the carbon source and ammonium as the nitrogen source. Ammonium limiting at a concentration of 3·75 mM. in the inflowing medium.			
1·01	0·35	1·66	3·10
0·88	0·71	1·30	2·42
0·79	1·14	0·87	1·62
0·44	1·78	0·23	0·43
0·29	1·83	0·18	0·33
0·00	2·01	0·00	0·00

* Values of R and P_e are averages of several determinations.

† This term is an estimate of the concentration of the limiting nutrient in units of population density. The quantity cS_0 is constant for each culture and equal to the value of P_e at R equal to zero.

‡ Estimates of this term were calculated by means of equation (2) in the text and are expressed as millimoles per l.

Table 2. *Relationship between specific growth rate* (R), *population density* (P_e), *and concentration of limiting nutrient* (S_e) *in continuous cultures of* Aerobacter aerogenes *at equilibrium**

R	P_e	$(cS_0 - P_e)$†	S_e‡
Culture 2 A. Succinic acid as the carbon source and ammonium as the nitrogen source. Succinic acid limiting at a concentration of 8·47 mM. in the inflowing medium.			
0·45	0·78	1·17	5·07
0·22	1·71	0·25	1·07
0·21	1·65	0·30	1·31
0·17	1·74	0·21	0·93
0·00	1·95	0·00	0·00
Culture 2 B. Succinic acid as the carbon source and ammonium as the nitrogen source. Succinic acid limiting at a concentration of 16·95 mM. in the inflowing medium.			
0·52	0·15	3·86	16·31
0·45	1·18	2·83	11·96
0·42	2·17	1·84	7·78
0·19	3·63	0·38	1·61
0·00	4·01	0·00	0·00

* Values of R and P_e are averages of several determinations.

† This term is an estimate of the concentration of the limiting nutrient in units of population density. The quantity cS_0 is constant for each culture and equal to the value of P_e at R equal to zero.

‡ Estimates of this term were calculated by means of equation (2) in the text and are expressed as millimoles per l.

Data from several experiments are given in Tables 1–3 and the relationships between R and P_e for each experiment are plotted in Fig. 2.

In cultures 3A and 3B (data of Table 3), determinations of the concentration of the limiting nutrient (ammonium) were made by two independent methods: (*a*) by means of equation (2) from estimates of P_e and cS_0; and (*b*) direct measurement of the concentration of ammonium. Figure 3 shows plots of estimates made by these two methods. The results confirm the relationship defined by equation (2) and show that the yield coefficient (the slope of the line in Fig. 3) is independent of specific growth rate.

Table 3. *Relationship between specific growth rate* (R), *population density* (P_e), *and concentration of limiting nutrient* (S_e) *in continuous cultures of* Aerobacter aerogenes *at equilibrium**

R	P_e	(cS_0-P_e)†	S_e‡
Culture 3A. Succinate as the carbon source and ammonium as the nitrogen source. Ammonium limiting at a concentration of 3·75 mM. in the inflowing medium.			
0·54	0·37	1·77	—
0·49	0·77	1·36	2·48
0·45	1·35	0·78	1·48
0·42	1·63	0·50	0·90
0·27	1·98	0·15	0·26
0·00	2·13	0·00	0·00
Culture 3B. Succinate as the carbon source and ammonium as the nitrogen source. Ammonium limiting at a concentration of 7·50 mM. in the inflowing medium.			
0·54	0·20	3·76	7·14
0·50	1·43	2·53	4·24
0·44	2·36	1·60	3·26
0·37	3·26	0·70	1·16
0·26	3·59	0·37	0·38
0·17	3·59	0·37	0·18
0·00	3·96	0·00	0·10

* Values of R, P_e, and S_e are averages of several determinations.

† This term is an estimate of the concentration of the limiting nutrient in units of population density. The quantity cS_0 is constant for each culture and equal to value of P_e at R equal to zero.

‡ Estimates of this term were made by direct chemical analysis and are expressed in millimoles per l.

Monod (1942) showed that the relationship between the specific growth rate of a bacterial population (R) and the concentration of a limiting nutrient (S) is approximately represented by

$$R = \frac{R_m S}{A+S}. \tag{4}$$

Parameters R_m and A are, respectively, the maximum specific growth rate of the culture and the concentration of the limiting nutrient when the specific growth rate is $\frac{1}{2}R_m$. The same relationship was found by Schaefer (1948) and by Longmuir (1954).

At equilibrium in continuous cultures, from equations (3) and (4),

$$D = R = \frac{R_m S_e}{A+S_e}, \tag{5}$$

where S_e is the concentration of limiting nutrient at equilibrium (Monod, 1950; Herbert *et al.* 1956; Moser, 1958). It is apparent from equation (5) that as S_e approaches S_0 and, from equation (2), as P_e approaches zero, R approaches a critical value R_c (see Herbert *et al.* 1956), where

$$R_c = \frac{R_m S_0}{A+S_0}. \tag{6}$$

Estimates of R_c can be obtained for each culture from the intersection on the y-axis of the curve giving R as a function of P_e (Fig. 2). Of particular interest is the fact that the estimates of R_c are the same for each culture with the same nitrogen and carbon sources, irrespective of the kind or concentration of the limiting nutrient. Thus, from equation (6), the ratio of the values of A for each of two such cultures is equal to the ratio of their values of S_0, or

$$\frac{A'}{A''} = \frac{S'_0}{S''_0}.$$

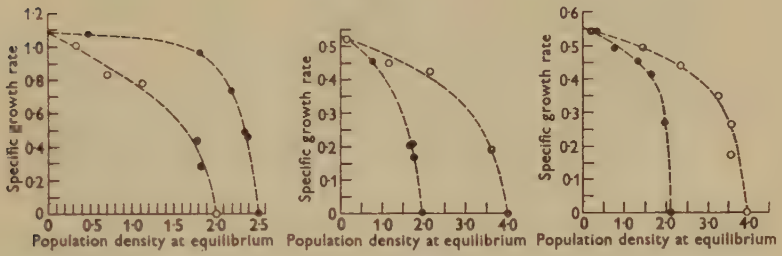


Fig. 2*a* Fig. 2*b* Fig. 2*c*

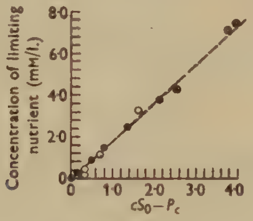


Fig. 3

Fig. 2*a*, *b* and *c*. Relationship between specific growth rate and population density of continuous cultures of *Aerobacter aerogenes* at equilibrium. (*a*) Data of Table 1; ● = culture 1A, glucose limiting at 5·55 mM. in inflowing medium; ○ = culture 1B, ammonium limiting at 3·75 mM. in inflowing medium, glucose as carbon source. (*b*) Data of Table 2; ● = culture 2A, succinate limiting at 8·47 mM. in inflowing medium; ○ = culture 2B, succinate limiting at 16·95 mM. in inflowing medium. (*c*) Data of Table 3; ● = culture 3A, ammonium limiting at 3·75 mM. in inflowing medium, succinate as carbon source; ○ = culture 3B, ammonium limiting at 7·50 mM. in inflowing medium, succinate as carbon source.

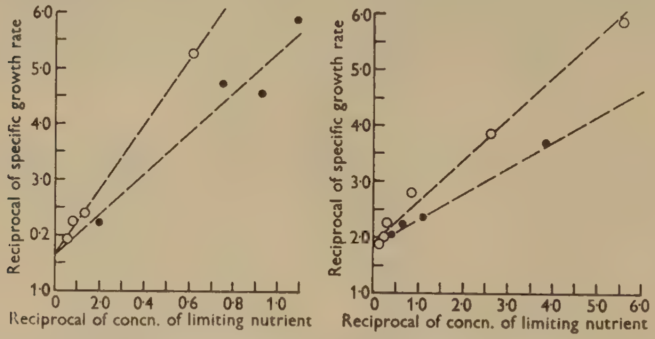
Fig. 3. Relationship between concentration of limiting nutrient (ammonium) and estimates of concentration of limiting nutrient in units of population density (cS_0-P_e) in continuous cultures of *Aerobacter aerogenes* at equilibrium. Data of Table 3; ● = culture 3A, ○ = culture 3B. See text for definitions of terms.

Since S_0 can be set at will, A must be a function of S_0.

Further evidence of this relationship is obtained from consideration of the data of Tables 2 and 3. Rearrangement of equation (5) gives

$$\frac{1}{R} = \frac{1}{R_m} + \left(\frac{A}{R_m}\right)\left(\frac{1}{S_e}\right). \tag{7}$$

If A is a function of S_0, $1/R$ should be a linear function of $1/S_e$ for each culture, but with slope dependent upon S_0. Figure 4 shows regressions of $1/S_e$ upon $1/R$ for the data of Tables 2 and 3 fitted by the method of least squares. The slopes of the regression lines are, respectively, 3·66 and 5·90 for cultures 2A and 2B; and 0·47 and 0·72 for cultures 3A and 3B. These results show that the values of A are correlated with S_0 in each instance and can be considered to be proportional to S_0, or



a *b*

Fig. 4*a* and *b*. Regression of reciprocals of the concentration of limiting nutrient upon reciprocals of specific growth rate in continuous cultures of *Aerobacter aerogenes*. (*a*) Data of Table 2; ● = culture 2A, ○ = culture 2B. (*b*) Data of Table 3; ● = culture 3A, ○ = culture 3B.

$$A = bS_0. \tag{8}$$

Dr A. Novick (personal communication) has pointed out that $A = a + b'S_0$ is a more realistic relationship in that on conversion of A into terms of P_e and S_e by equation (2) and substitution into equation (4) a model is obtained that is better behaved at small values of P_e. However, the precision of the data is not good enough to determine whether or not a is real. Moreover, equation (8) is sufficient for the purposes of this discussion since a, even if real, would be quite small compared to the values of bS_0 in these experiments.

Substituting equation (8) into (7) gives, therefore,

$$\frac{1}{R} = \frac{1}{R_m} + \left(\frac{bS_0}{R_m}\right)\left(\frac{1}{S_e}\right) \tag{9}$$

and, from equation (2) and letting $(1+b)/R_m = 1/u_m$ and $b/cR_m = B/u_m$,

$$\frac{1}{R} = \frac{1}{u_m} + \left(\frac{B}{u_m}\right)\left(\frac{P_e}{S_e}\right). \tag{10}$$

Equation (10) requires that the reciprocal of the specific growth rate should be a linear function of the ratio of population density to concentration of limiting nutrient. Plots of $1/R$ versus P_e/S_e for the data of Tables 1–3 are given in Fig. 5, and confirm the relationship given by equation (10). The different slopes of Fig. 5*a* arise from the fact that the limiting nutrient is different in each culture.

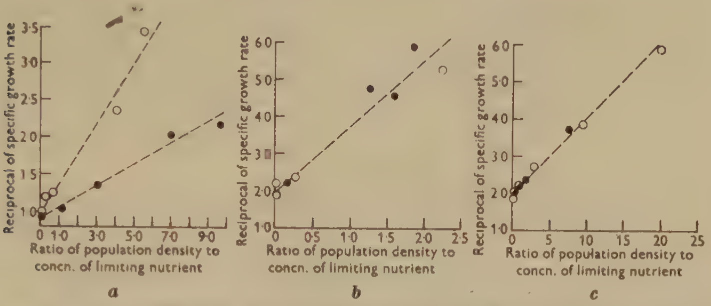


Fig. 5 *a*, *b* and *c*. Relationship between reciprocals of specific growth rate and ratios of population density to concentration of limiting nutrient in continuous cultures of *Aerobacter aerogenes* at equilibrium. (*a*) Data of Table 1; ● = culture 1A, ○ = culture 1B. (*b*) Data of Table 2; ● = culture 2A, ○ = culture 2B. (*c*) Data of Table 3; ● = culture 3A, ○ = culture 3B. ◒ indicates two points at the same locus.

Rearrangement of equation (9) gives

$$R = \frac{R_m S}{bS_0 + S} \tag{11}$$

and equation (10) gives

$$R = \frac{u_m S}{BP + S}. \tag{12}$$

DISCUSSION

Monod (1942), in deriving equation (4), and others, who subsequently used this relationship, considered parameter A to be independent of population density. Most of Monod's data, however, was obtained from experiments in which specific growth rates were measured at the beginning of growth cycles of batch cultures with different concentrations of limiting nutrient and in which initial population densities were the same from culture to culture. His results could be explained by equation (12) since, with population density essentially constant, equation (12) would reduce to equation (4). In studies of batch cultures where specific growth rates and concentrations of limiting nutrient were measured throughout the entire growth cycle, the relationship between specific growth rate and nutrient concentration for each culture could be expressed by equation (11); since, with initial concentration of limiting nutrient constant in each instance, equation (11) also reduces to equation (4).

Although the results of this study show that parameter A—the concentration of the limiting nutrient when the specific growth rate is half maximum—is a function of population density, the data provide no insight into the origin of or reason for this relationship. Other workers have attributed deviations of continuous cultures from Monod's model (equation (4)) to 'apparatus effects' such as incomplete or 'imperfect' mixing of the inflowing medium with the culture and wall-growth (Herbert *et al.* 1956). Although 'perfect' mixing is difficult to attain in continuous culture devices with large culture volumes, the small culture volumes (30–45 ml.) and the methods of mixing and introduction of medium used in these studies would preclude incomplete mixing as a factor responsible for the observed results. Further tests, which consisted of introducing drops of a dye solution into the culture vessels, showed that mixing was completed in only 2 or 3 sec. As previously mentioned, no wall-growth was observed in any of these experiments.

The point could be legitimately raised that the observed relationship between population density and parameter A might be due to consequential changes in environmental conditions as population density becomes large, or to the possibility that oxygen may become limiting at high growth rates (cf. Pirt, 1957). The author believes that these factors were not operative in these studies since the observed growth parameters for each culture were independent of population density, nutrient concentration and specific growth rate. Also, under comparable conditions they were reproducible from culture to culture independently of the concentration of the limiting nutrient in the inflowing medium. The results observed in these experiments might be attributable to an inhibition of the growth process by end-products of that process. Since the yield coefficient is independent of specific growth rate in each culture, the concentrations of soluble end-products of the growth process probably are related to P (or S_0) in a simple manner. Thus the appearance of P in equation (12) may be due to what is primarily an effect of concentration of end-products.

The nature of equation (11) (or (12)) is such that, discounting lag, so-called logarithmic growth could never occur in batch cultures. However, parameter b is small for most cultures; and, as a result, with population density small and concentration of limiting nutrient relatively large (conditions usually extant in 'young' batch cultures) growth could be considered logarithmic for all practical purposes over a considerable time interval. For example, an organism growing in batch culture with an initial population density of 1×10^6 organisms/ml., cS_0 equal to 2×10^9 organisms/ml., R_m equal to 0·5 hr.$^{-1}$, and b equal to 0·1 would have an initial specific growth rate (by equation (11)) of 0·454. After *c.* 10 hr. of growth and at a population density of 1×10^8 organisms/ml. the specific growth rate would still be 0·452.

In conclusion, it is believed that equations (11) and (12) serve as adequate models for bacterial growth in both batch and continuous cultures and are more realistic than other models proposed previously. By substitution of equation (12) into equation (3) and integrating with dilution rate constant, a relationship is obtained which shows that population density and concentration of limiting nutrient approach constant values in time which are unique

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for each dilution rate less than the maximum specific growth rate. This accounts for the relationship between specific growth rate and population density at equilibrium that has been observed in this and other studies (see Herbert *et al.* 1956) and the fact that equilibrium is even attained by continuous cultures.

The author wishes to express his thanks and appreciation for the interest, encouragement and helpful suggestions given by Drs Claude ZoBell and Carl Eckart of the University of California, La Jolla; and the financial aid granted by the Steering Committee of the Marine Life Research Program of the University of California.

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REFERENCES

Bail, O. (1929). Ergebnisse experimenteller Populationsforschung. *Z. Immun-Forsch.* **60**, 1.

Contois, D. E. (1957). *Kinetics of Microbial Growth. Theory and Applications.* Ph.D. thesis, University of California, Los Angeles.

Dagley, S. & Hinshelwood, C. N. (1938). Physicochemical aspects of bacterial growth. I. Dependence of growth of *Bact. lactis aerogenes* on concentration of medium. *J. chem. Soc.* p. 1930.

Greenleaf, W. E. (1926). The influence of volume of culture medium and cell proximity on the rate of reproduction of infusoria. *J. exp. Zool.* **46**, 143.

Herbert, D., Elsworth, R. & Telling, R. C. (1956). The continuous culture of bacteria: a theoretical and experimental study. *J. gen. Microbiol.* **14**, 601.

Lawrence, J. V. (1957). Bacterial growth and food supply. *Bact. Proc.* **57**, 63.

Lodge, R. M. & Hinshelwood, C. N. (1939). Physicochemical aspects of bacterial growth. IV. Considerations determining stationary populations and growth rates of *Bact. lactis aerogenes* in synthetic media. *J. chem. Soc.* p. 1683.

Longmuir, I. S. (1954). Respiration rate of bacteria as a function of oxygen concentration. *Biochem. J.* **57**, 81.

Monod, J. (1942). *Recherches sur la Croissance des Cultures Bactériennes.* Paris: Hermann et Cie.

Monod, J. (1950). La technique de culture continué. Théorie et applications. *Ann. Inst. Pasteur*, **79**, 390.

Moser, H. (1958). The dynamics of bacterial populations maintained in the chemostat. *Publ. Carneg. Instn*, no. 614.

Novick, A. & Szilard, L. (1950). Description of the chemostat. *Science*, **112**, 715.

Pearl, R. & Parker, S. L. (1922). On the influence of density of population upon the rate of reproduction in *Drosophila*. *Proc. nat. Acad. Sci., Wash.* **8**, 212.

Pirt, J. (1957). The oxygen requirement of growing cultures of an *Aerobacter* species determined by means of the continuous culture technique. *J. gen. Microbiol.* **16**, 59.

Schaefer, W. (1948). Recherches sur la croissance du *Mycobacterium tuberculosis* en culture homogené. *Ann. Inst. Pasteur*, **74**, 458.

Spicer, C. C. (1955). The theory of bacterial constant growth apparatus. *Biometrics*, **11**, 225.

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MACRO-INVERTEBRATE ASSEMBLAGES OF CENTRAL TEXAS COASTAL BAYS AND LAGUNA MADRE

BY

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MACRO-INVERTEBRATE ASSEMBLAGES OF CENTRAL TEXAS COASTAL BAYS AND LAGUNA MADRE[1]

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ABSTRACT

A study of the distribution of macrofauna and the ecological factors affecting their distribution in the bays and lagoons of the central and south Texas coast has made it possible to formulate a series of criteria for interpreting modern and ancient depositional environments. The observations reported in this paper cover a 7-year period. In addition, some information was available covering a period of 30 years. The central Texas bays are situated in a variable climate, and the faunas reflect long-term changes in rainfall and temperature.

Four major environments are recognized on the basis of macro-invertebrate assemblages: (1) river-influenced low-salinity bays and estuaries characterized by *Rangia* and amnicolids; (2) enclosed bays, dominated by oyster reefs composed of *Crassostrea virginica;* (3) open bays and sounds characterized by *Tagelus divisus*, *Chione cancellata*, and *Macoma constricta;* and (4) bay and lagoon regions strongly influenced by inlets characterized by a mixed Gulf and bay fauna. Smaller "sub-facies" needing more information for recognition are: (1) bay margins, (2) oyster reefs exhibiting marine influence, (3) bay centers, and (4) shallow grassy bays in the vicinity of inlets.

Five assemblages were recognized in Laguna Madre which are related to the physiography of the Laguna Madre: (1) shallow hypersaline area near inlet characterized by forms common to the Gulf and normal salinity bays on the north; (2) open hypersaline lagoon characterized by *Amygdalum papyria* and other forms attaching to vegetation; (3) enclosed hypersaline lagoon with tremendous numbers of two pelecypods, *Anomalocardia cuneimeris* and *Mulinia lateralis;* (4) relatively deep hypersaline bay with clayey substrate with virtually no living macro-invertebrates; and (5) hypersaline lagoon with normal bay influence, occupied by many of the species typical of an open bay plus *Anomalocardia* and *Mulinia.*

The application of macrofaunal assemblages to the interpretation of older sediments was demonstrated in a study of a series of borings taken in the Rockport area. The macrofaunal evidence indicates that the Rockport bays have undergone at least one marine transgression in the past 9,000 years.

INTRODUCTION[3]

The purpose of this study is to establish criteria for the identification of shallow-water marine environments based on the distribution of the present-day macro-invertebrates, which may be useful in interpreting the ancient depositional environments. A previous study in the Mississippi Delta region (Parker, 1956) established macrofaunal criteria for the recognition of sedimentary environments in an area of rapid deposition, comparatively high rainfall and extremely variable hydrography. The Rockport, Texas, area (Fig. 1), with low rainfall, a slow rate of deposition and comparatively stable hydrography was selected as a contrasting depositional setting. The sediments, microfauna, and geologic setting of the Rock-

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[2] Scripps Institution of Oceanography, University of California.

[3] Most of the past and present staff of the American Petroleum Institute Project 51 have assisted in collecting and analyzing the data which are used in the report. The writer is particularly grateful to W. K. Emerson and E. L. Puffer for permission to make use of their data. Among the staff, past and present, of the Marine Laboratory of the Texas Game and Fish Commission at Rockport, Texas, who have contributed considerable time and information are Howard T. Lee, Cecil Reed, Joseph Breuer, William Guest, Robert Hofstettor, H. Hoese, Ernest Simmons, and Terrance Leary. At Scripps Institution, considerable assistance and advice were given by Joseph R. Curray, William Fager, Joel W. Hedgpeth, Fred B Phleger, Gene A. Rusnak, Francis P. Shepard, and T. J. Van Andel. Robert Winsett, Howard Taylor and James R. Moriarty prepared the illustrations.

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port region have been discussed by other investigators (Shepard and Moore, 1955; Shepard, 1953, 1956; F. L. Parker, Phleger and Peirson, 1953; Phleger, 1956; Phleger and Lankford, 1957; and Swain, 1955).

Studies were also carried out in the Laguna Madre of Texas (Fig. 1). This area provides an even greater contrast to the Mississippi Delta, both in hydrography and fauna. The sediments, hydrography, and geologic history of the Laguna Madre are discussed by Rusnak (in press).

The investigation of the macro-invertebrate assemblages of the Rockport, Texas, bays was initiated by this project in 1951 by Puffer (1953) and Puffer and Emerson (1953). Most of their work was based on one set of samples taken over a 6-week period in July and August, 1951. Preliminary studies indicated to the writer that a sampling program of such a short duration would be insufficient to give a detailed picture of bay assemblages.

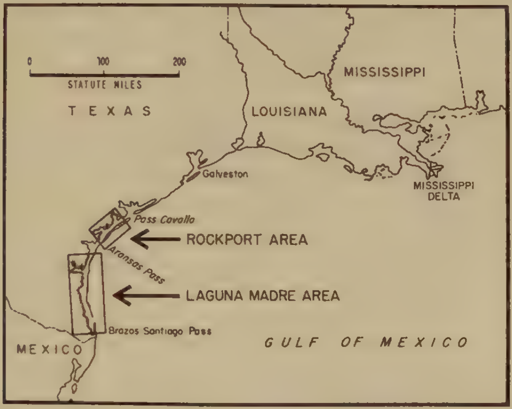

FIG. 1.—Location of study areas on coast of northwest Gulf of Mexico.

The Rockport region, 30 miles northeast of Corpus Christi, includes several shallow connected bays, separated from the open Gulf of Mexico by wide barrier islands, occasionally interrupted by very narrow inlets (Fig. 2). During the present study these bays have remained relatively free of pollution or human disturbance, except from numerous oil wells in Copano Bay (not studied in detail) and the dredging of semi-fossil oyster reefs in San Antonio Bay. The bays in this area are well suited for a study of the effects of environmental factors, particularly salinity, on the distribution of invertebrates, since there is a wide range of salinity from river mouth to open Gulf.

Numerous papers have been published on the faunal assemblages present in Texas under climatic conditions different from those of the past 7 years. These papers have been useful in interpreting the presence of the large amount of shell

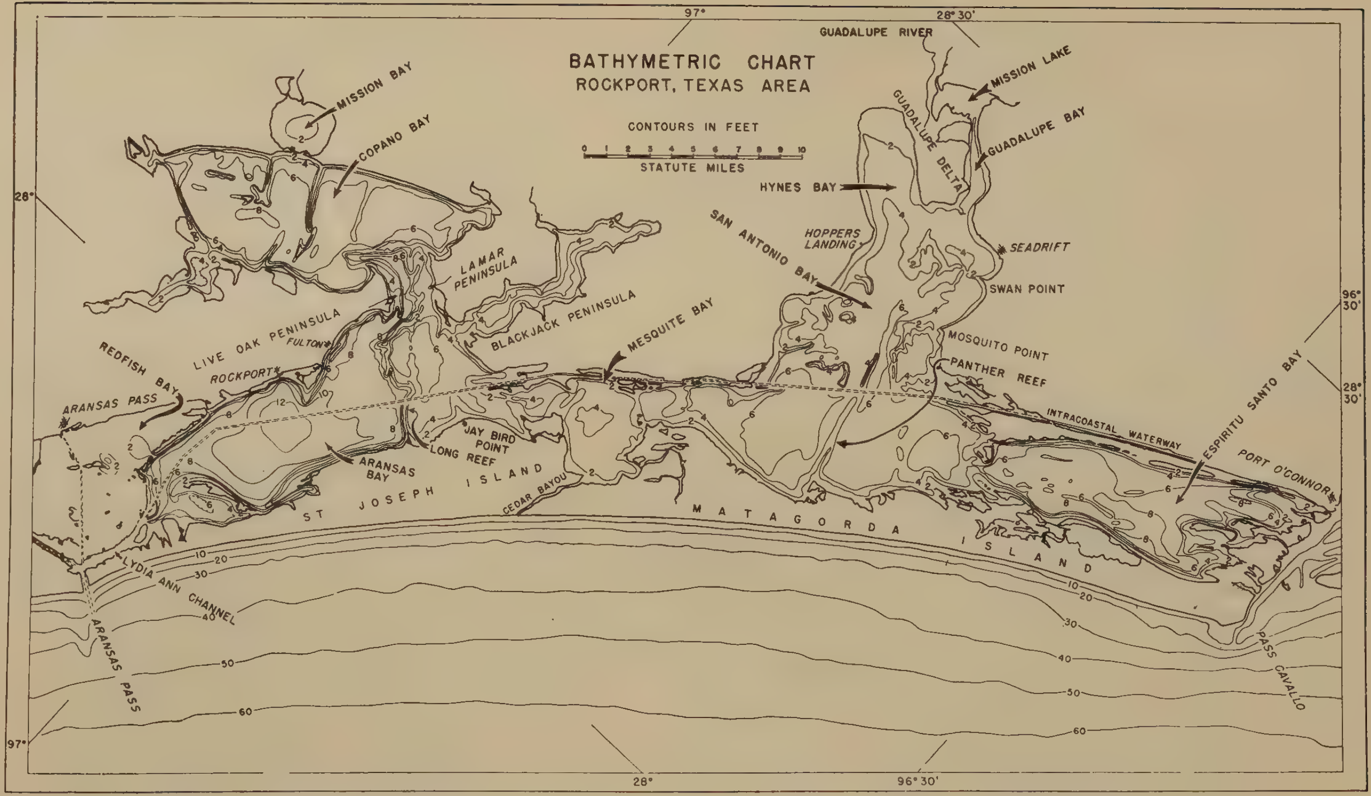
BATHYMETRIC CHART
ROCKPORT, TEXAS AREA
CONTOURS IN FEET
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES
97°
28° 30'
28°
96° 30'
GUADALUPE RIVER
MISSION LAKE
GUADALUPE BAY
GUADALUPE DELTA
HYNES BAY
SAN ANTONIO BAY
HOPPERS LANDING
SEADRIFT
SWAN POINT
MOSQUITO POINT
PANTHER REEF
INTRACOASTAL WATERWAY
ESPIRITU SANTO BAY
PORT O'CONNOR
PASS CAVALLO
MATAGORDA ISLAND
MISSION BAY
COPANO BAY
LAMAR PENINSULA
BLACKJACK PENINSULA
MESQUITE BAY
LIVE OAK PENINSULA
FULTON
ROCKPORT
REDFISH BAY
ARANSAS PASS
JAY BIRD POINT
LONG REEF
ARANSAS BAY
ST JOSEPH ISLAND
CEDAR BAYOU
LYDIA ANN CHANNEL
ARANSAS PASS
10
20
30
40
50
60

FIG. 2.—Bottom topography and locality names, Rockport area. Bay contour interval 2 feet. (After Shepard and Moore, 1955)

material not found living during the present study (Mitchell, 1894; Galtsoff, 1931; Gunter, 1950; Pulley, 1952; Ladd, 1951; and Hedgpeth, 1953). Except for Mitchell's study, the other surveys were carried out when salinity values were considerably lower than during the period covered by this study. The hydrography of the Rockport region during times of reduced salinity is discussed by Collier and Hedgpeth (1950) and discussion of the high salinity values obtained in the early stages of the present study may be found in Hildebrand and Gunter (1953), Puffer and Emerson (1953), and Parker (1955). Extensive bibliographies on the geology, biology, and ecology of the central Texas coast can be found in Hedgpeth (1953), Galtsoff *et al.* (1954), Shepard and Moore (1955), and Ladd, Hedgpeth, and Post (1957). A geographic and geologic description of the Rockport region is given in Shepard and Moore (1955) and the post-Pleistocene-Recent history of the area has been discussed by Shepard (1956).

METHODS

Salinity measurements were taken intermittently throughout the period of study (Mohr method of titration and hydrometer). The majority of salinity measurements made since 1954 were made at the Marine Laboratory of the Texas Game and Fish Commission, while others were obtained as part of a seasonal study of Foraminifera (Phleger, 1956). Other physical and chemical measurements are given by Shepard and Moore (1955, pp. 1491–98, 1519–28).

During the first few years of the project, biological samples were taken with the "orange-peel" grab and otter trawl. Although not used for quantitative bottom sampling, these devices obtained large enough samples for a reconnaissance survey of the area. During the latter half of the study, the Van Veen bottom grab and minidredge replaced the previous sampling gear. As in similar work in the Mississippi Delta region (Parker, 1956), the coarse fraction of the sediment from the top 10–20 cm. of cores taken for the geological studies was analyzed to obtain information on the past range of many species not found alive at the time of sampling. Samples were also taken by beachcombing and wading along the shores, especially in the shallow Redfish Bay area.

Most of the invertebrates were identified by the writer and checked at the U. S. National Museum, Washington, D. C., and the Museum of Comparative Zoology, Harvard University. The invertebrates collected during the 1951 field season were identified and checked by Puffer and Emerson.

The number of living and dead individuals of each species of mollusk, echinoderm, crustacean, and certain coelenterates was determined for all biological samples, except for the samples taken by Puffer and Emerson and the staff of the Marine Laboratory at Rockport. Most of the indicator species were found at more than 9 stations, and taken alive at more than 30 per cent of the stations falling within the boundary of the environment for which each was thought to be indicative. It must be stressed, however, that no one or two indicator species by themselves can be considered a positive criterion for environmental interpretation. There is a subjective element in interpretation, since it is the character (comparative abundance of living and dead of a number of species) of the assemblage which has a specific "appearance," that can not be expressed in quantitative terms. All species with more than 9 station occurrences were plotted on small distribution maps, and the centers of abundance of these populations selected. These distribution maps were then compared with the known variance of physical and chemical factors, as well as published distributions of the fauna at times of reduced salinity and high rainfall. These basic data permit the establishing of faunal boundaries, which may fluctuate considerably. The environmental boundaries were established from the observations of both physical and biological data.

Tables with all of the invertebrate species with their station occurrences and comparative abundance are on file at the Library of Scripps Institution of Oceanography.

ENVIRONMENTAL DESCRIPTION OF ROCKPORT AREA

The Rockport region is a suitable one for the study of the faunas in relation to environmental factors, as there are records of the distribution of temperature and salinity from 1926 (Galtsoff, 1931) to the present time. A detailed study of the hydrography of the Rockport area was made by Collier and Hedgpeth (1950) during the period from 1936 through 1946, and the salinity and temperature data from 1946 to 1953 have been discussed by Parker (1955). Restricted hydrographic surveys have also been carried out from 1953 to 1957 by members of the A.P.I. Project 51 staff, and the staff of the Marine Laboratory at Rockport. Since there is very little communication between these bays and the Gulf of Mexico, it is possible to observe the effects of high river discharge and lowered salinity, and conversely, low river discharge, high evaporation rate, and resultant hypersalinities. In both extreme cases, most of the bay system becomes essentially isohaline; while intermediate cases of runoff produce a series of salinity regimes, ranging from very low salinities at the river mouths to normal Gulf salinities at the entrance of the various inlets.

Salinity.—The central Texas bays are considerably more stable than the Mississippi Delta region in regard to short-period salinity variations, although the total range of salinity is much greater. Salinity measurements in the Delta region ranged from about 2 to 36°/₀₀, while in the Rockport area salinity values ranged from less than 1 to more than 42°/₀₀. If the Laguna Madre is included, the upper range of salinity measured is about 114°/₀₀. In the Mississippi Delta, these variations take place in periods ranging from a few days to a few weeks, and the increase from low to high takes place over a fairly short distance. In the Rockport region, the change from low to high salinity usually takes place over a period of several years, although a change from high to low may occur suddenly, as in the spring of 1957 when salinity in Mesquite and Aransas bays dropped from over 40°/₀₀ to as low as 2–4°/₀₀ in less than 3 weeks. The gradual rise in salinity permits the invasion of the bays by a marine fauna, whereas the sudden drops in salinity cause mass mortalities.[4] Both of these phenomena have been recorded during this study.

In order to visualize the general circulation patterns in the Rockport area, it is best to examine surface isohaline maps from several different climatic periods. The first attempt to establish the pattern of the distribution of salinity in the Aransas-San Antonio Bay system was made by Galtsoff (1931) who published a series of isohalines for the period between January and February, 1926. These isohalines (Fig. 3) reflect an intermediate estuarine situation comparable with Pritchard's (1952) definition of a positive coastal plain estuary, in which river runoff and precipitation exceed evaporation. Salinities ranged from 4°/₀₀ at the mouth of San Antonio-Guadalupe River to 27°/₀₀ at Aransas Pass, and reflected high rainfall, but not flood conditions, in the drainage basin. Collier and Hedgpeth (1950) established a similar set of isohalines in Aransas Bay for March, 1937 (Fig. 4), indicating similar climatic conditions. Examination of 30 years salinity records for these bays shows the positive estuarine situation to be the prevalent one for the Rockport bay system.

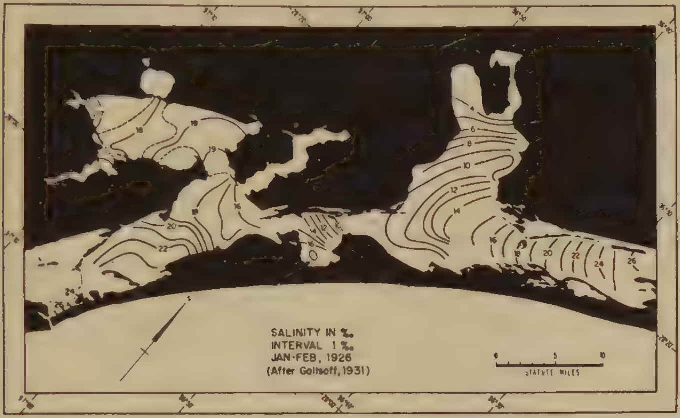

FIG. 3.—Surface isohalines during period of "average" rainfall. Contour interval 1°/₀₀. Dashed line interval 0.5°/₀₀.

Extreme flood conditions have been recorded several times, the most severe by Collier and Hedgpeth on July 14, 1936, when salinities ranged between 3 and 5°/₀₀ throughout Aransas Bay, and San Antonio and Copano bays were virtually fresh. Similar conditions also occurred in May, 1938, June, 1941, October, 1946,

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[4] This point has been disputed by Ladd, Hedgpeth, and Post (1957, pp. 603–04), but it should be pointed out that the present study includes four times the number of stations, occupied over a considerably longer period than that discussed by Ladd.

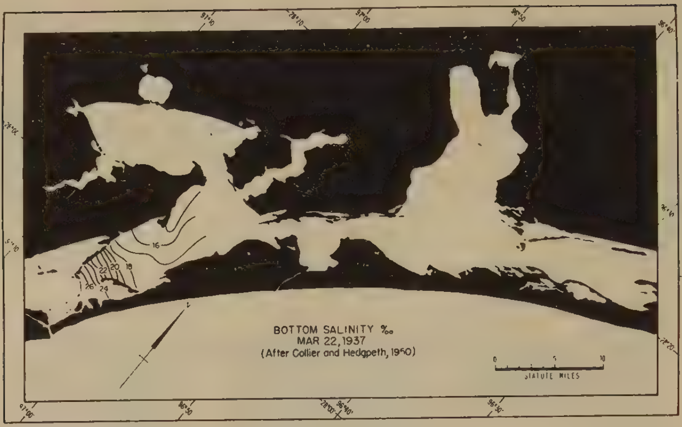
16
18
20
22
24
26
BOTTOM SALINITY ‰
MAR 22, 1937
(After Collier and Hedgpeth, 1950)
0
5
10
STATUTE MILES
N
97°00'
96°50'
28°00'
96°40'
96°30'
28°20'

Fig. 4.—Bottom isohalines during period of "average" rainfall, stressing reduced salinities in vicinity of Aransas Pass. Contour interval 1°/₀₀.

and in June, 1957 (Fig. 5). A particularly great destruction of fauna requiring high salinity for optimum living conditions was observed during the June, 1957, flood. This was to be expected, as bay salinities preceding the flood were approximately 40°/₀₀, whereas salinities preceding the earlier floods were much lower. Since high-salinity faunas had not become so firmly established in the upper bays prior to earlier floods, mass mortalities of marine invertebrates were not of the magnitude of that which occurred in 1957.

The distribution of salinity in the Rockport bays during drought conditions

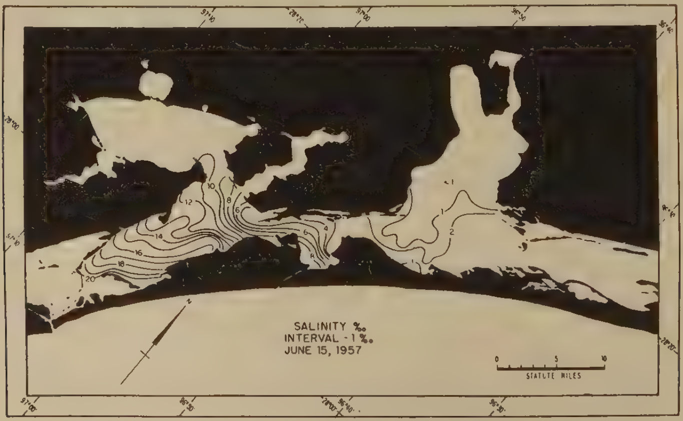
1
2
4
6
8
10
12
14
16
18
20
SALINITY ‰
INTERVAL - 1 ‰
JUNE 15, 1957
0
5
10
STATUTE MILES
N
97°00'
96°50'
28°00'
96°40'
96°30'
28°20'

Fig. 5.—Surface isohalines immediately after major flood in drainage basin.

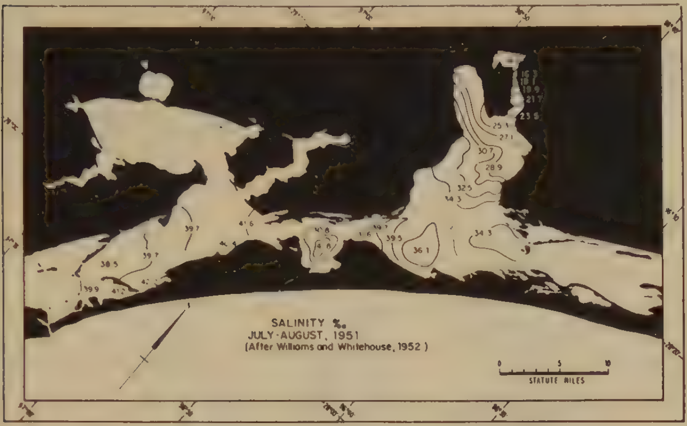
SALINITY ‰
JULY-AUGUST, 1951
(After Williams and Whitehouse, 1952)
0
5
10
STATUTE MILES

FIG. 6.—Surface isohalines during severe drought period.

has been discussed by Phleger (1956) and Parker (1955). The salinity patterns existing in the early stages of the recent Texas drought (Williams and Whitehouse, 1952) show a uniform salinity distribution in Aransas Bay of about 40°/₀₀, but a considerable spread of values from 14 to 42°/₀₀ in San Antonio Bay (Fig. 6). Salinity values obtained by Phleger and Lankford in November, 1954, at a later stage of the drought (Fig. 7) show a spread of values from 24°/₀₀ at the river's mouth to 36.8°/₀₀ in Mesquite Bay, with a difference of only 2°/₀₀ from the cen-

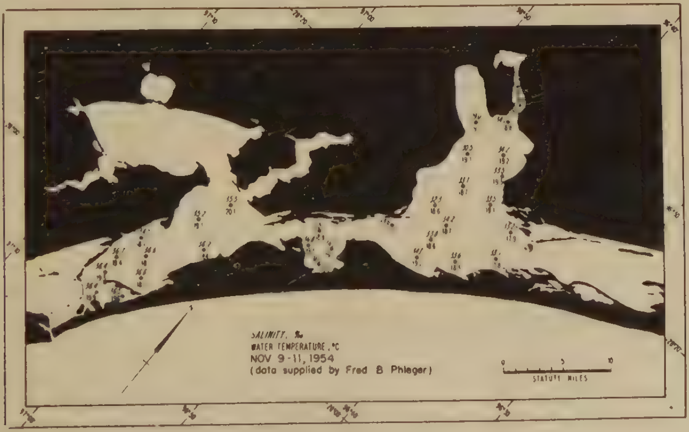
SALINITY, ‰
WATER TEMPERATURE, °C
NOV 9-11, 1954
(data supplied by Fred B Phleger)
0
5
10
STATUTE MILES

FIG. 7.—Distribution salinity and temperature during drought, showing virtually an isohaline condition throughout. (After Phleger and Lankford)

TABLE I. RANGE OF PHYSICAL CHARACTERISTICS, ROCKPORT AND LAGUNA MADRE

Environment	*Physical Factor*	*Rockport Area*	*Laguna Madre*
Marshes and Shores	Depth	0 to 1 ft.	Shore to 6 in.
	Salinity	0 to 7°/oo	36 to 60°/oo
	Water temp.	0 to 37°C.	5 to 40°C.
	Bottom sediments	Sand	Sand
	Currents	—	—
	Morphology*	IX	IX
River Influence, Low Salinity	Depth	1 to 4 ft.	Absent
	Salinity	1 to 30°/oo	
	Water temp.	1 to 34°C.	
	Bottom sediment	Clayey silt, silty clay	
	Currents	Weak	
	Morphology	IV and VI	
Enclosed Bays Low to Variable Salinity	Depth	1 to 6 ft.	Absent
	Salinity	3 to 40°/oo	
	Water temp.	10 to 34°C.	
	Bottom sediment	Silty clay, sand-silt-clay	
	Currents	Weak	
	Morphology	II	
Low-Salinity Living Reefs	Depth	1 to 3 ft.	Absent
	Salinity	3 to 40°/oo	
	Water temp.	10 to 34°C.	
	Bottom sediment	Shell	
	Currents	Weak	
	Morphology	VIII	
High-Salinity Living Reefs	Depth	1 to 15 ft.	Absent
	Salinity	5 to 41°/oo	
	Water temp.	4 to 34°C.	
	Bottom sediment	Shell, sandy shell	
	Currents	Weak to strong	
	Morphology	VII and VIII	
Open High-Salinity Bay and Sound Centers	Depth	5 to 12 ft.	3 to 5 ft.
	Salinity	5 to 41°/oo	23 to 42°/oo
	Water temp.	4 to 34°C.	9 to 33°C.
	Bottom sediment	Silty clay	Sand, silty sand, clayey sand
	Currents	Weak	Weak
	Morphology	III (modified)	V
Open High-Salinity Bay and Sound Margins	Depth	1 to 5 ft.	1 to 3 ft.
	Salinity	3 to 42°/oo	23 to 69°/oo
	Water temp.	3 to 36°C.	9 to 36°C.
	Bottom sediment	Sand, sand-silt-clay	Sand, silty sand
	Currents	Weak to strong	Weak
	Morphology	III	V

* Morphologic types from Price, 1947.

I. Long narrow enclosed lagoon, length 3 to 4 times width.
II. Enclosed basins of oval shape, most shorelines curving.
III. Enclosed segment of coastal lagoons.
IV. Embayment of drowned valleys.
V. Segment separated by bars and spits.
VI. Unfilled part of alluvial plain.
VII. Narrow deep channels.
VIII. Submerged bars, usually aligned perpendicular to the circulation.
IX. Narrow fringing marsh and shoreline, not inundated.

Types VII, VIII, and IX originated by the writer. Sediment types from Shepard, 1954.

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TABLE I—(*Continued*

Environment	*Physical Factor*	*Rockport Area*	*Laguna Madre*
Inlets, Inlet Influence	Depth	5 to 22 ft.	3 to 30 ft.
	Salinity	11 to 36‰	30 to 40‰
	Water temp.	10 to 34°C.	9 to 30°C.
	Bottom sediment	Sand, shelly sand	Sand
	Currents	Strong	Strong
	Morphology	VII	VII
Enclosed Hypersaline Bays	Depth	Absent	1 to 5 ft.
	Salinity		23 to 80‰
	Water temp.		9 to 36° C.
	Bottom sediment		Sand, shelly sand
	Currents		Weak
	Morphology		I
Open, Shallow Hypersaline Bays	Depth	1 to 2 ft.	1 to 4 ft.
	Salinity	20 to 42‰	23 to 80‰
	Water temp.	3 to 36° C.	9 to 36° C.
	Bottom sediment	Clayey sand	Sand, shelly sand
	Currents	Weak	Weak
	Morphology	V	I
Relatively Deep Hypersaline Bays	Depth	Absent	1 to 8 ft.
	Salinity		2 to 102‰
	Water temp.		9 to 30° C.
	Bottom sediment		Clay
	Currents		Weak
	Morphology		IV

ter of San Antonio Bay to the Gulf of Mexico (similar to Pritchard's "neutral estuary"). Although a few surveys taken during this prolonged drought indicated occasional tongues of low-salinity water in lower San Antonio Bay, the rest of the bay system was isohaline at normal sea water values or above. It can be seen, therefore, that drought conditions in Texas bays convert the bays from the normal positive estuarine condition to Pritchard's inverse estuarine condition in which evaporation exceeds river runoff and precipitation. Salinity ranges for each of the Rockport bay environments are tabulated in Table I, which gives the range of physical variables for the bay areas covered in this study.

Temperature.—The distributional patterns of water temperature and salinity in the Rockport bays show close similarity; i.e., changes in water temperatures from the inlet to the river mouth correspond with similar changes in salinity from inlet to river mouth. Temperature distributional patterns have been discussed in detail by Collier and Hedgpeth (1950) and more recently by Phleger (1956) and Parker (1955). An example of areal distribution of water temperature in the Rockport area throughout 2 years of sampling can be found in Phleger (1956, pp. 98–99). In summer, lower temperatures and lower salinities are found in the deeper parts of the bays, whereas higher water temperatures occur simultaneously with hypersalinities in the very shallow parts of the bays. This is a result of excessively high summer air temperatures and consequent evaporation. In winter, when air temperatures may drop below freezing, and ice occasionally forms at the edges of the lower-salinity bays, the higher water temperatures are found in the deeper parts of the bays, generally associated with the tidal movement of warmer Gulf water into the bays. The water temperature differences from one end of the bay system to the other are small (Fig. 7), and day-to-night differences in one place may be greater than those between inlet and river.

Only the long period and seasonal fluctuations of air temperature and resultant differences in water temperature are of value in assessing the effect of temperature on the distribution of invertebrates in the bays. In the past 60 years there have been periods of severe winters with prolonged freezes and lower winter temperatures, alternating with periods of at least 6 years with no freezing air temperatures and warmer winters. These sudden freezes when ice was observed around the edges of Copano and St. Charles bays (the last of which was observed in January, 1951) have had considerable effect upon the composition of faunal assemblages in the Rockport area (Gunter and Hildebrand, 1951). Temperature ranges for the Rockport bay environments are given in Table I.

Sediments.—Maps of the distribution of sediment units have been prepared or published for the bays of the Rockport area and the Laguna Madre. Most of the sediment maps used in this study have a sediment textural nomenclature developed by A.P.I. Project 51 and published by Shepard (1954). This system is based entirely on proportions of sand, silt, and clay as represented in the triangular diagram (Fig. 8). The sediment distribution map for the Rockport area (Fig. 8) was originally published in Shepard and Moore (1955). The Rockport bay sediments consist of silty clays in the deep central parts of the bays, grading into a mixed zone of sandy clay, clayey sand, or sand-silt-clay at intermediate depths, and a narrow zone of bordering sands in the shallowest depths where there is considerable wave action. This general arrangement of sediments from fine in the center to coarse materials at the bay margins is locally complicated by variations in source, topography, placement of large oyster reefs, and water circulation, resulting in somewhat different arrangement of sediments such as shown in lower San Antonio and Mesquite bays (Fig. 8). The sediment types most representative of the Rockport bay biological environments are also given in Table I.

Currents.—A brief discussion of currents and wind velocity data obtained by this Project may be found in Shepard and Moore (1955, pp. 1481–93). A hypothetical circulation of the bays in the Rockport area can be postulated from a composite of the distribution of salinity values at different times of high and low river discharge, wind direction, and tides (Fig. 9). A suggestion of possible circulation patterns in Aransas Bay was also offered by Collier and Hedgpeth (1950, p. 151). These patterns were deduced from the isohalines and isotherms at various stages of the tide, although no current measurements were made at that time. Velocities of slightly more than 1.2 knots were obtained in Aransas Pass by A.P.I. Project 51 personnel, when winds were blowing either north or south at more than 8 knots.

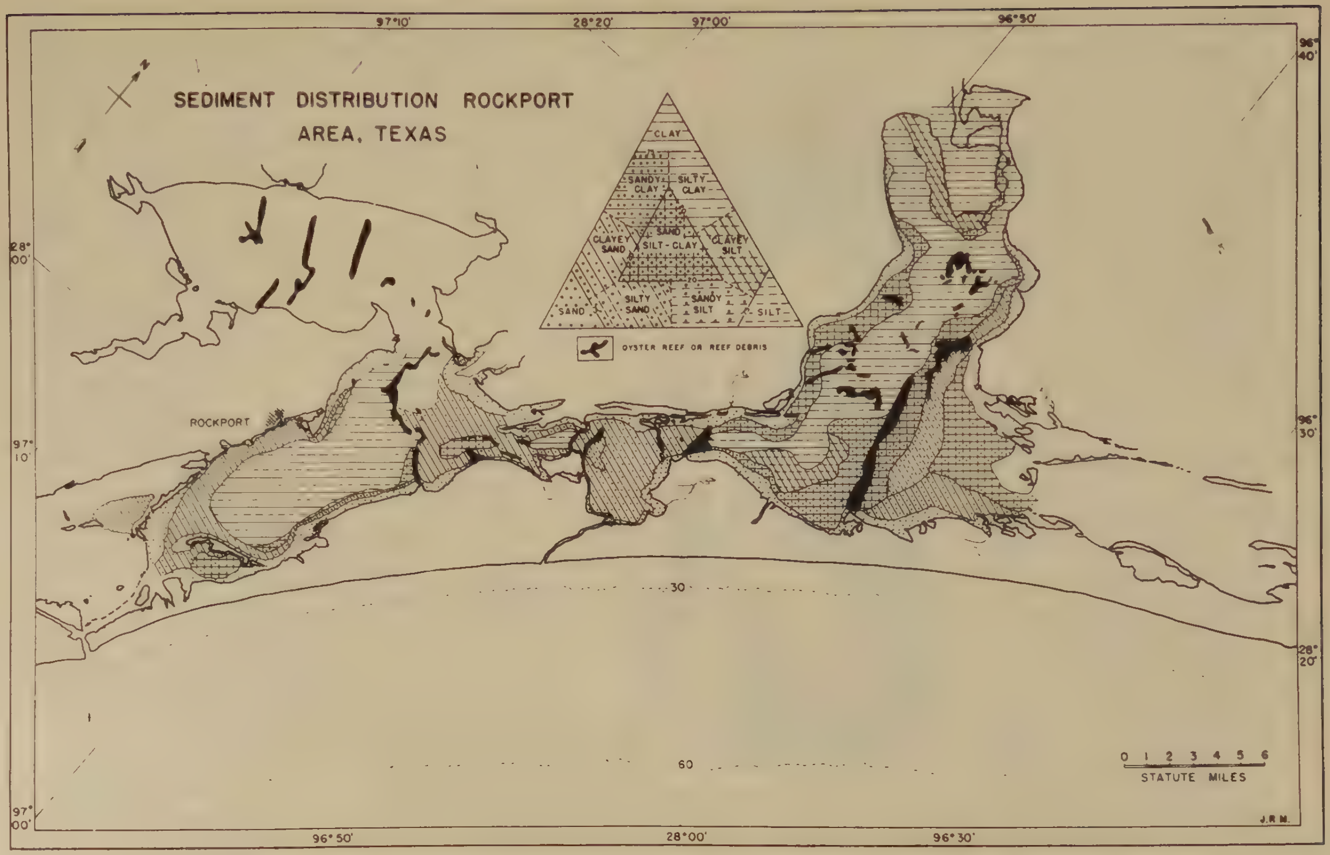

SEDIMENT DISTRIBUTION ROCKPORT AREA, TEXAS
CLAY
SANDY CLAY
SILTY CLAY
CLAYEY SAND
SAND SILT-CLAY
CLAYEY SILT
SAND
SILTY SAND
SANDY SILT
SILT
OYSTER REEF OR REEF DEBRIS
ROCKPORT
30
60
0 1 2 3 4 5 6
STATUTE MILES
97°10'
28°20'
97°00'
96°30'
96° 40'
28° 00'
97° 10'
96° 30'
28° 20'
97° 00'
96°50'
28°00'
96°30'
J.R.M.

FIG. 8.—Sediment distribution, Rockport area, based on percentages of sand-silt-clay. (After Shepard and Moore, 1955)

Measurements of current velocity at the entrance to Copano Bay in Aransas Bay indicated a current moving out of Copano Bay in response to a northeast wind, at a velocity of .17–.37 knot. Currents strong enough to lay channel markers horizontal were also observed in the "land cut" of the Intracoastal Waterway between San Antonio Bay and Aransas Bay concurrent with prolonged "northers" and high river discharge into San Antonio Bay. The direction was always from San Antonio Bay to the deeper Aransas Bay. This current is indicated by the isopleths for Aransas Bay for June, 1957 (Fig. 5), showing a plume of low-salinity water flowing from the entrance of the Intracoastal Waterway into Aransas Bay. Strong currents were also observed in Lydia Ann Channel during periods of strong winds from the north and south. These currents emanating from Lydia Ann Channel, tend to dissipate as the water empties into Aransas Bay. The high-salinity or Gulf water moves into the bay, first along the shores of Aransas Bay, and then into the middle of the bay, as can be seen by examining the isohalines of Aransas Bay in Figures 3–7.

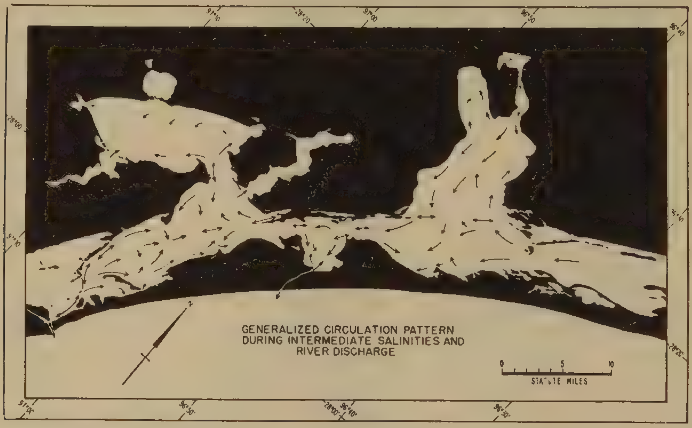

GENERALIZED CIRCULATION PATTERN
DURING INTERMEDIATE SALINITIES AND
RIVER DISCHARGE
0
5
10
STATUTE MILES

FIG. 9.—Generalized circulation. Direction of arrows dependent on stage of tide and wind direction. Length of arrows indicates comparative current strength.

This semi-permanent circulation of Gulf water along the shores, rather than in the bay center is borne out by the presence of predominantly Gulf invertebrates at the bay margins, and their absence in the center or upper reaches of Aransas Bay throughout most of the period of observation. Along with wave action, this type of circulation is probably instrumental in depositing the coarser sediments into narrow bands paralleling the shorelines of both St. Joseph Island and the Live Oak Peninsula.

Since many of the characteristic species composing the assemblages cited in this paper have pelagic or free-living larval stages, it can be seen that the movement of water is extremely important in determining the assemblage of deposition. An excellent discussion concerning the factors influencing larval settlement and the composition of benthic communities can be found in Thorson (1958, pp. 479–89). As the larvae are transported in almost the same manner as sediment grains, it is no wonder there is such a close correlation between sediment types and faunal distribution. Papers have been written by European biologists on the transportation of larval mollusks by currents, and the close correlation between current strength and direction, sediment types, and the size and composition of benthic populations (Kreger, 1940; Baggerman, 1953; and Verwey, 1952). It is also significant that the circulation of bay waters is in part a reflection of the physiography or shape of the bays. Under some conditions water movement actually creates some of the topographic features such as sand bars and channels. Because the water circulation, shoreline, and bottom topography are so closely interrelated, it can be seen that there is good reason for certain macrofaunas appearing to be indicators of sedimentary environments and marine topography.

According to Hedgpeth (personal communication) the movement of water is strongest along the north shore, which is characterized by a much wider band of coarse sediments (Fig. 8). The comparative current strengths for each of the biological environments in the Rockport area are given in Table I.

MACRO-INVERTEBRATE ASSEMBLAGES

Since most bay or lagoon deposits contain far more dead shell material than living fauna, it was felt that both the living and dead assemblages should be discussed, and then be combined into the assemblage of deposition. It is also necessary to discuss the living assemblages in relation to the climate and hydrography existing at the time of sampling, and thus be in a better position to explain the presence of shell remains of forms not living at the time of sampling. In the Rockport area, this means separating the living assemblages found during wet periods and low salinity, from those found during droughts and high salinity. This task was not too difficult since extensive faunal lists have been compiled in this region from 1892 to the present time. Lists of the organisms collected during the past 60 years and their collectors may be found in Parker (1955).

ASSEMBLAGES OF ROCKPORT REGION

Although the environmental boundaries in the Rockport bays tend to fluctuate considerably over the years, the assemblages characterizing these environments are distinct. The information used to establish these faunal assemblages was obtained from 400 biological stations taken during this study (Figs. 10a and 10b) and 71 stations taken as part of Ladd's (1951) study (Fig. 11). In the present study, a broad environmental concept is presented which may have an application to ancient sedimentary environments where the paleontologist has only a few widely spaced samples for analysis. Within the larger bay environments, smaller "sub-facies" are also demonstrated which should be of some use to the biologist or geologist studying Recent sediments, or to the paleontologists using large num-

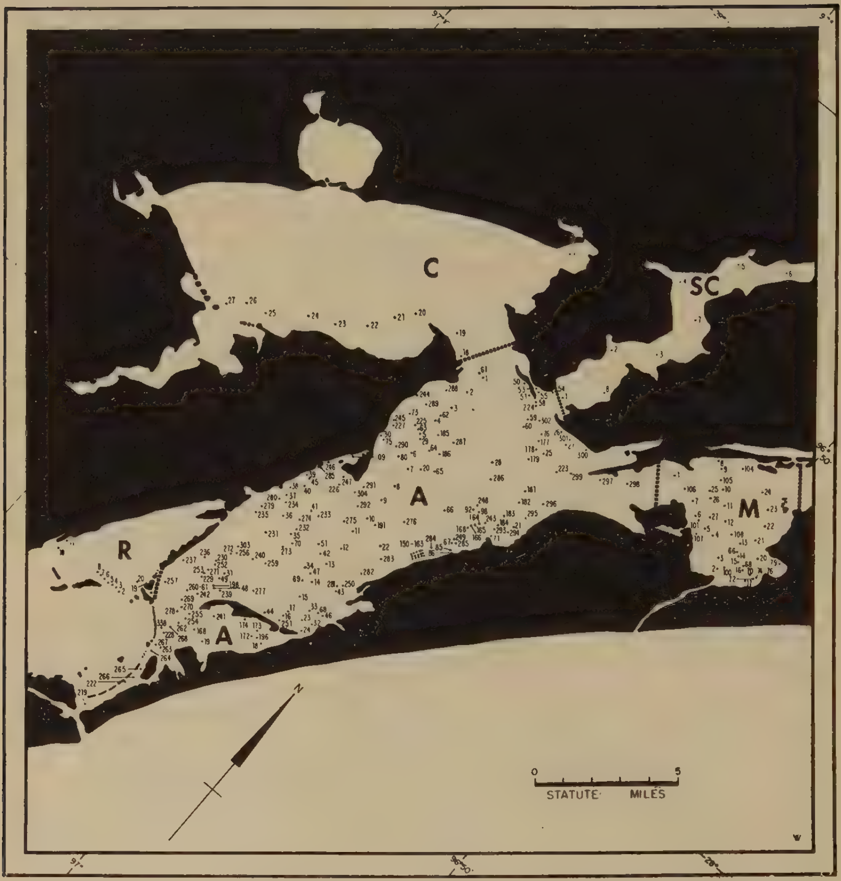


FIG. 10a.—Location of biological samples, Aransas Bay and vicinity (1951–57). Stations within area bounded by dashed lines take prefix of block letter.

bers of closely spaced samples. The major biological assemblages of the Rockport bays and associated minor assemblages (Figs. 12a and 12b) are discussed. Because the boundaries of these environments and associated assemblages change considerably with large-scale climatic changes, it was necessary to construct two environmental or facies maps. One (Fig. 12a) shows the areal extent of the environments during prolonged low salinity, and the other (Fig. 12b) shows the same environmental coverage during prolonged high salinity. The salinity connotations in the environmental titles, describe the environment, and do not infer that salinity is the only controlling factor. The distribution of the dead shell in these

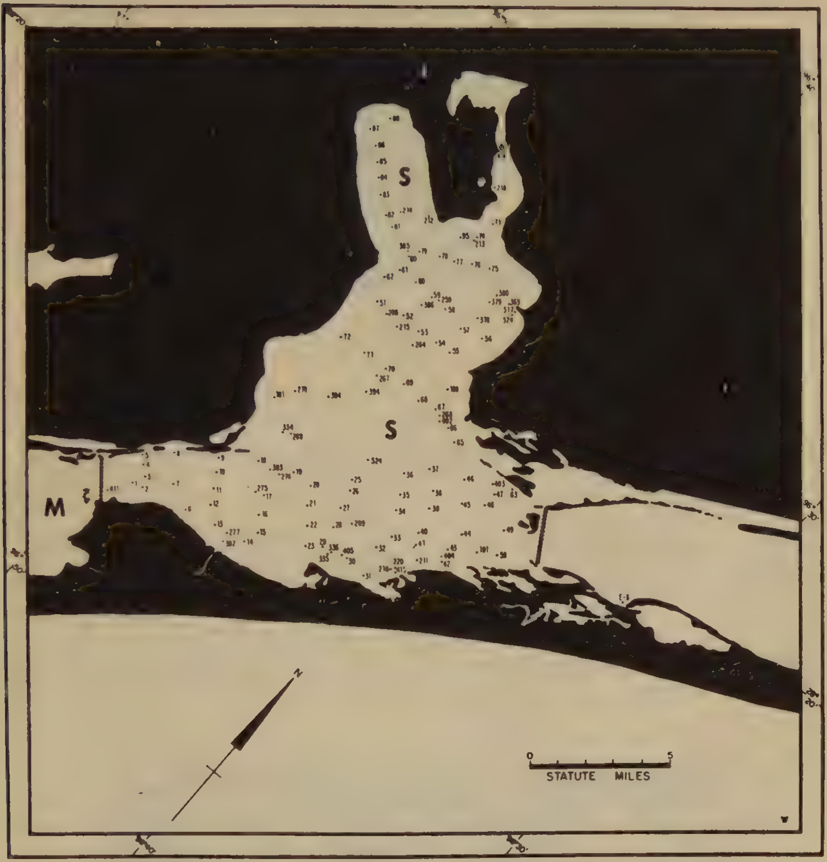


FIG. 10b.—Location of biological samples, San Antonio Bay and vicinity (1951–57). All stations on this chart prefixed by S, except E-8 in Espiritu Santo Bay.

bays is an indication of the extent of low-salinity influence during periods not sampled during this study.

I. *River-influenced, low-salinity assemblage.*—The part of the Rockport bay system characterized by the low-salinity or river-influenced fauna is small in comparison with that in the Mississippi Delta region (Parker, 1956) and in some of the large bays and sounds on the north and east. Only a small part of San Antonio Bay and perhaps parts of Copano Bay are continually freshened by the rather small rivers which empty into these bays. As can be seen in Figures 12a and 12b, the boundary of this environment fluctuates considerably with the

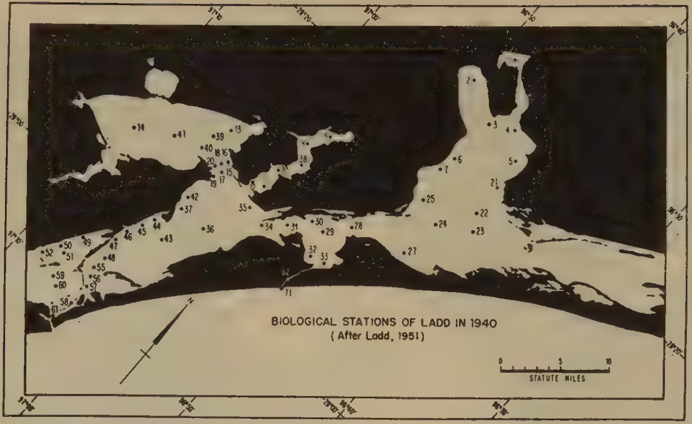

BIOLOGICAL STATIONS OF LADD IN 1940
(After Ladd, 1951)
0
5
10
STATUTE MILES
N

Fig. 11.—Location of biological samples taken by Ladd in 1940.

changing hydrography. At the time of Ladd's (1951) study when salinities throughout the Rockport bays were considerably below normal Gulf salinity of 36°/₀₀, this environment (called the "bay head facies" by Ladd) included Mission Bay (part of Copano Bay), parts of St. Charles Bay and half of San Antonio Bay. During the recent drought, this assemblage was eliminated completely from Copano Bay and St. Charles Bay, as well as from a large part of San Antonio Bay. From the faunal distribution in the past and present time, it can be postulated that salinity is one of the more important factors influencing the assem-

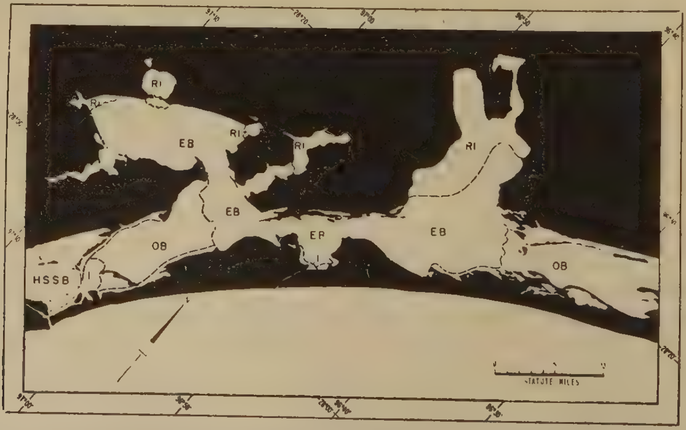

RI
R
EB
RI
RI
RI
EB
OB
EP
EB
OB
HSSB
I
STATUTE MILES

Fig. 12a.—Boundaries of macro-invertebrate assemblages during period of high rainfall. HSSB—high-salinity shallow bay; I—inlet; OB—open bay; EB—enclosed bay; RI—river-influenced, low salinity.

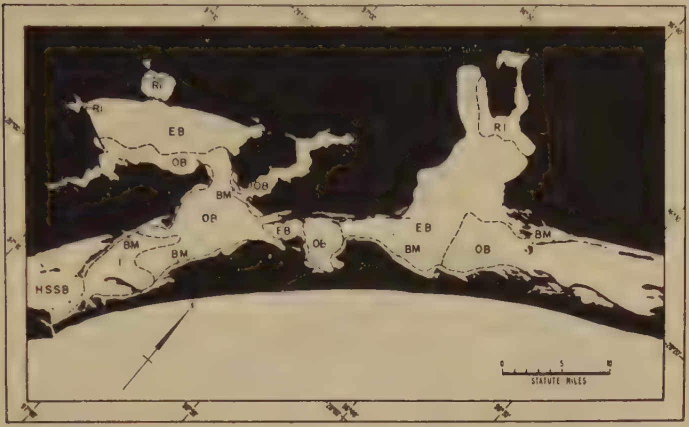


FIG. 12b.—Boundaries of macro-invertebrate assemblages during droughts and high salinity. HSSB—hypersaline shallow bay; I—inlet; BM—bay margin; OB—open bay center; EB—enclosed bay; RI—river-influenced.

blages in this environment, although river-borne nutrients and high turbidity and associated fine sediments may also be important. Circulation is also important in determining the distribution of the low-salinity fauna. Most of the river water flows along the western shore of San Antonio Bay, and likewise the majority of the living representatives of low-salinity species are also found along this shore, being conspicuously absent from the opposite shore. The physical factors characteristic of this environment are given in Table I.

The low-salinity environment is a difficult one for the survival of true marine animals, and only five species of invertebrates are known to thrive there, characterizing low-salinity areas along most of the northern Gulf coast. The boundaries of this environment, based on an average of the ranges of the indicator species and environmental factors are shown in Figure 13a, demonstrated by the distribution of the pelecypod, *Rangia cuneata* and Figure 13b, by the distribution of the pelecypod, *Macoma mitchelli*. From the distribution of dead shell of both of these species, it can be seen that low-salinity conditions must have been far more widespread in the past than during the period the area was sampled by Ladd and the writer. The presence of these forms mixed with an enclosed-bay assemblage in slightly older deposits suggests that low and intermediate salinities alternated with considerable frequency. The other two invertebrate species typical of this environment are the gastropod, *Littoridina sphinctostoma*, and the river shrimp, *Macrobrachium ohione* (reported by Hedgpeth, 1949). The pelecypod, *Mulinia lateralis*, is also found in river-influenced areas, but is by no means characteristic of this environment. The Rockport river-influenced fauna are tabulated in Table II in the Appendix, which lists all of the invertebrates by environment. Representative specimens of these species are figured on Plate I.

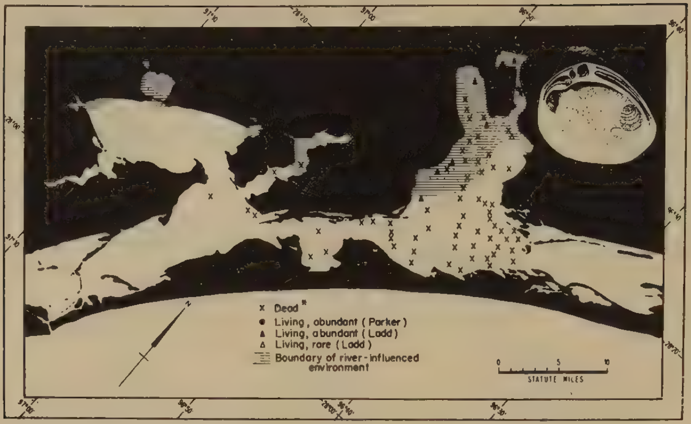

x Dead *
● Living, abundant (Parker)
▲ Living, abundant (Ladd)
△ Living, rare (Ladd)
Boundary of river-influenced environment
0 5 10
STATUTE MILES
N

FIG. 13a.—Distribution of pelecypod, *Rangia cuneata*, most abundant during times of low salinity and high rainfall.

II. *Enclosed bays of variable low to intermediate salinities, characterized by oyster reefs.*—The enclosed-bay environment corresponds roughly with Ladd's (1951) "reef and inter-reef facies" during times of low salinity, but it is more difficult to define when the bays are essentially isohaline. This environment characterizes the major parts of the Rockport bays; although the faunal composition may change considerably with long-period changes in salinity and temperature. Its boundaries include all of the major oyster reefs, since these biological units re-

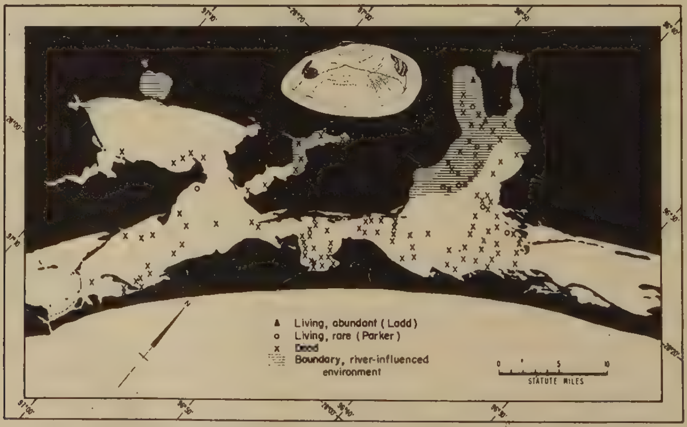

▲ Living, abundant (Ladd)
o Living, rare (Parker)
x Dead
Boundary, river-influenced environment
0 5 10
STATUTE MILES
N

FIG. 13b.—Distribution of pelecypod, *Macoma mitchelli*, most abundant during times of low salinity and high rainfall.

main intact and soon become repopulated after periods of adverse salinity conditions. The oyster reefs also act as natural barriers to the circulation, thus serving to isolate this environment from the high-salinity parts of the bays, as well as the river-influenced areas. Exclusive of the oyster-reef assemblage, which is a sub-assemblage and is discussed separately, only seven species of invertebrates can be considered characteristic (in terms of abundance) of the level-bottoms between the oyster reefs. However, a number of species from the high-salinity waters may migrate into the "inter-reef" area at times of high salinity. The superimposed distribution of two of the more characteristic invertebrates, Figure 14a, the pelecypod, *Mulinia lateralis*, and Figure 14b, the brittle star, *Amphiodia limbata*, illustrate the extent of the enclosed-bay environment. Apparently *Mulinia* is less dependent on gross salinity changes, as the distribution of living and dead specimens during both Ladd's and the present survey show excellent agreement. *Mulinia* is also common in the other environments, but its presence elsewhere is not significant, as there are many more abundant species and individuals in the other environments. No comparison of the distribution of *Amphiodia* at different salinity periods was possible, as it was not cited dead or alive by Ladd. The fauna typical of the enclosed bay areas of variable salinity is as follows.

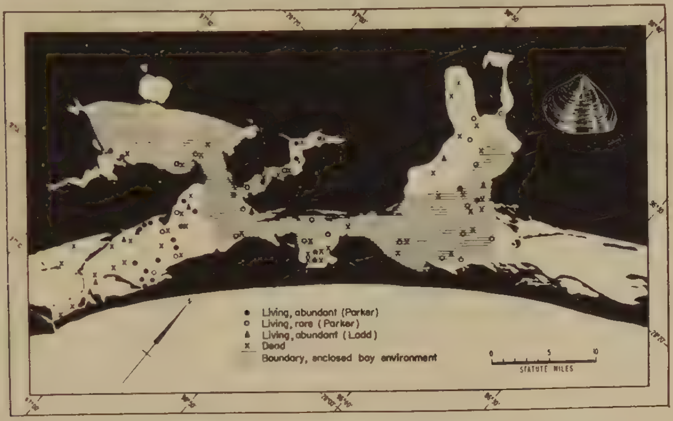

● Living, abundant (Parker)
○ Living, rare (Parker)
▲ Living, abundant (Ladd)
x Dead
Boundary, enclosed bay environment
0
5
10
STATUTE MILES

FIG. 14a.—Distribution of pelecypod, *Mulinia lateralis*, most abundant during times of low to variable salinity.

GASTROPODS
Retusa canaliculata (Say, 1827)

PELECYPODS
Ensis minor Dall, 1899
Mulinia lateralis (Say, 1822)
Nuculana acuta (Conrad, 1834)
Nuculana concentrica (Say, 1824)
Tagelus plebeius (Solander, 1786)

ECHINODERMS
Amphiodia limbata (Grube)

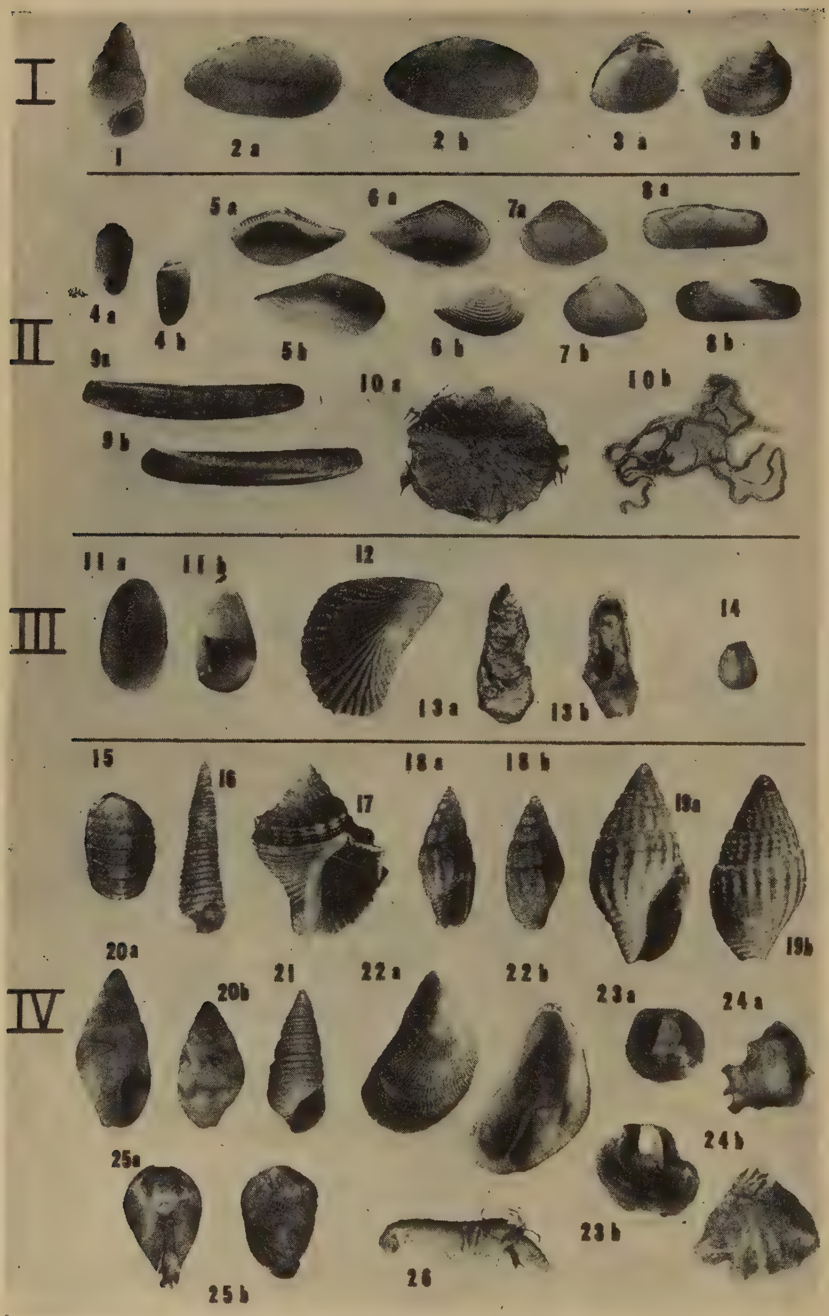

I
1
2 a
2 b
3 a
3 b
II
4 a
4 b
5 a
5 b
6 a
6 b
7a
7 b
8 a
8 b
9a
9 b
10 a
10 b
III
11 a
11 b
12
13 a
13 b
14
IV
15
16
17
18 a
18 b
19a
19b
20a
20b
21
22 a
22 b
23 a
23 b
24 a
24 b
25a
25 b
26

PLATE I

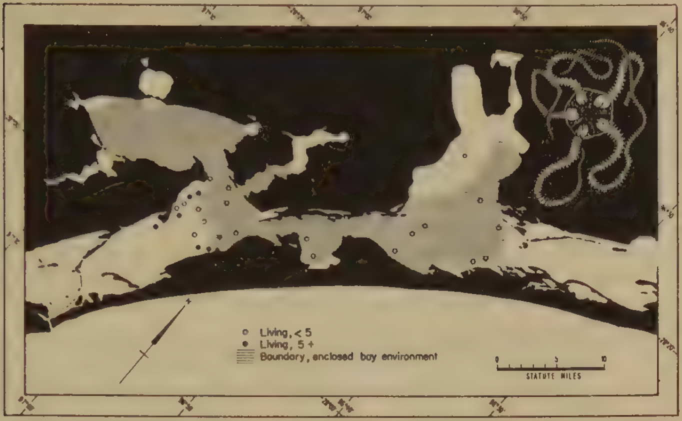


FIG. 14b.—Distribution of brittle star, *Amphiodia limbata*, taken only during period of high salinity. Although occurrences are shown in Aransas Bay, as outside the environmental boundary, most are within the physiographic boundary of the enclosed part of that bay.

←«««

PLATE I

I. RIVER-INFLUENCED, LOW-SALINITY ASSEMBLAGE

1. *Littoridina sphinctostoma*, size—3×2 mm., aperture.
2. *Macoma mitchelli*, size 21×12 mm., a. interior, b. exterior.
3. *Rangia cuneata*, size 42×39 mm., a. interior, b. exterior.

II. ENCLOSED BAYS, VARIABLE LOW TO INTERMEDIATE SALINITIES

4. *Retusa canaliculata*, size—6×3 mm., a. aperture, b. back.
5. *Nuculana concentrica*, size—11×6 mm., a. interior, b. exterior.
6. *Nuculana acuta*, size—6×4 mm., a. interior, b. exterior.
7. *Mulinia lateralis*, size—10×7 mm., a. interior, b. exterior.
8. *Tagelus plebeius*, size—42×16 mm., a. interior, b. exterior.
9. *Ensis minor*, size—54×10 mm., a. interior, b. exterior.
10. *Amphiodia limbata*, disc diameter—6 mm., a. disc, b. ventral side.

III. LOW-SALINITY OYSTER REEF

11. *Crepidula plana*, size—22×12 mm., a. back, b. interior (aperture).
12. *Brachidontes recurvus*, size—16×11 mm., exterior.
13. *Crassostrea virginica*, size—170×70 mm., a. exterior, b. interior.
14. *Balanus eburneus*, size—6×5 mm. side view.

IV. HIGH-SALINITY SHELL REEF

15. *Ischnochiton pappilosa*, size—3×2 mm., exterior.
16. *Seila adamsi*, size—6×1 mm., aperture.
17. *Thais haemastoma floridana*, size—47×29 mm., aperture.
18. *Anachis avara semiplicata*, size—11×5 mm., a. aperture, b. back.
19. *Anachis obesa*, size—4×2 mm., a. aperture, b. back.
20. *Mitrella lunata*, size—4×2 mm., a. aperture, b. back.
21. *Odostomia impressa*, size—3×1 mm., aperture.
22. *Brachidontes exustus*,'size—17×9 mm., a. exterior, b. interior.
23. *Amoxia simplex*, size—21×20 mm., a. interior (top value, b. interior, attached valve).
24. *Ostrea equestris*, size—19×14 mm., a. interior, b. exterior.
25. *Diplothyra smithi*, size—6×4 mm., a. dorsal, b. side.
26. *Crangon heterochelis*, size—37 mm., side view.

The physical factors characterizing this environment in the Rockport area are given in Table I, and all of the invertebrate species taken in this environment are given in Table II in the Appendix.

Low-salinity oyster reef.—Although this assemblage is part of the enclosed-bay environment, it is the dominant group of organisms, and contributes most of the shell material in the inter-reef deposits. *Crassostrea virginica*, the bay oyster, forms the greater part of the reef, while the other invertebrates attach to the surface of the oysters, either competing for food or feeding on the oysters themselves. In the northern Gulf of Mexico, the bay oyster flourishes and builds its reefs in shallow water, many of them perpendicular to the prevailing currents under what appear to be ideal conditions: a firm bottom, salinities ranging from about 12 to 25$^{\circ}/_{oo}$ (which will exclude most of the fouling organisms), and temperatures cool enough in winter to permit cessation of reproductive activities, so that they may devote their energies to growth. The Rockport area does not provide these "ideal" conditions for oyster growth at the present time, but there is considerable evidence that this has not always been the case. Most of the modern reefs extend in depth to at least 14 feet below the surface of the sediment (Norris, 1953), and subsurface borings in San Antonio Bay indicated reefs dating about 9,000 years old, as deep as 80 feet below the surface (Shepard and Moore, 1955, pp. 1555–59). Marine Sonoprobe records in Corpus Christi Bay a few miles south of Rockport, also show buried reefs presumed to be oysters, with thicknesses of 60–80 feet (McClure, Nelson, and Huckabay, 1958). At present, the Rockport oyster reefs are primarily composed of dead shell with very few live oysters attached. The faunal composition of the oyster reefs during times of reduced salinity is simple, and usually stabilized for long periods of time in such areas as western Louisiana and east Texas.

It should also be noted that the shape of *Crassostrea* is generally diagnostic of certain environmental conditions as noted by Gunter (1938). On hard bottom and uncrowded beds, the shells are thick, curved to the right, and almost as wide as long. When growing on soft or rapidly silting bottom, in shallower water and crowded conditions, shells are generally very long, straight, and thin. *Crassostrea virginica* living in higher than normal salinities exhibits very thin, crenulated and highly colored lips (Parker, 1955).

The invertebrate species found on the Rockport reefs during stable low salinities are as follows.

GASTROPODS
Crepidula plana Say, 1822
PELECYPODS
Brachidontes recurvus (Rafinesque, 1820)
Crassostrea virginica (Gmelin, 1791)
CRUSTACEANS
Balanus eburneus Gould, 1841
Balanus amphitrite niveus Darwin, 1854

Other invertebrates become part of the oyster-reef assemblage whenever salinities rise to more than 25 $^{\circ}/_{oo}$ for any extended period (Puffer and Emerson, 1953), and may eventually become so abundant as to retard the activities of the dominant *Crassostrea virginica*. At stable high salinities, the gulf oyster, *Ostrea equestris*, may completely replace the bay oyster, but because of its small size may never form large reefs. In June, 1957, there was an opportunity to observe the effect of suddenly reduced salinities upon *Ostrea equestris*. During the recent drought *Ostrea equestris* became the dominant oyster on the reefs in the Rockport area, but when salinities dropped to a low of 1–5°/₀₀, all of the *O. equestris* died in Aransas Bay proper, Mesquite Bay, and San Antonio Bay. The organisms cited in the paper by Puffer and Emerson (1953) are those typical of an oyster or shell reef living in high salinities near an inlet or in an open sound, and are listed here with additional species taken by this writer.

GASTROPODS
Anachis avara semiplicata (Stearns, 1873)
Anachis obesa (C. B. Adams, 1845)
Mitrella lunata (Say, 1826)
Odostomia impressa (Say, 1821)
Seila adamsi (H. C. Lea, 1846)
Thais haemastoma floridana (Conrad, 1837)

CHITONS
Ischnochiton papillosa (C. B. Adams, 1845)

PELECYPODS
Anomia simplex d'Orbigny, 1842
Brachidontes exustus (Linné, 1758)
Diplothyra smithi (Tryon, 1862)
Ostrea equestris Say, 1834

BRYOZOA
Bugula, species
Membranipora, species

CRUSTACEANS
Crangon heterochelis (Say)
Menippe mercenaria (Say)

Figure 15 shows the distribution of both kinds of oyster reefs in the Rockport region. The characteristic physical factors are given in Table I, and representative specimens of most of the species characteristic of enclosed bays and

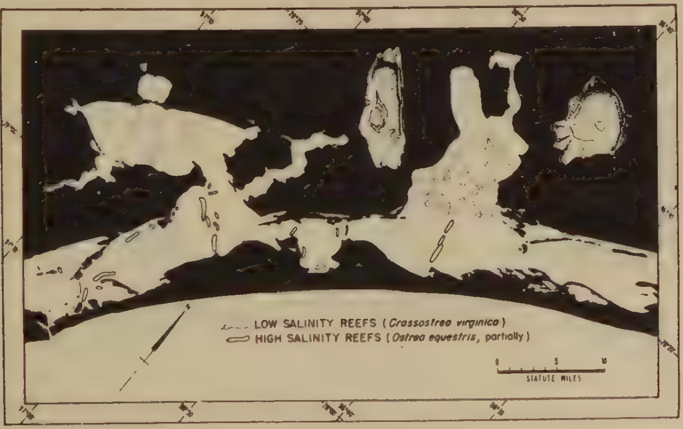

LOW SALINITY REEFS (Crassostrea virginica)
HIGH SALINITY REEFS (Ostrea equestris, partially)
0
5
10
STATUTE MILES

FIG. 15.—Distribution of low-salinity reefs in Rockport area, illustrated by long, narrow "coon" oysters, *Crassostrea virginica*. High salinity reefs are typified by *Ostrea equestris*, the small round oyster, with crenulated margin and teeth on inside of margin.

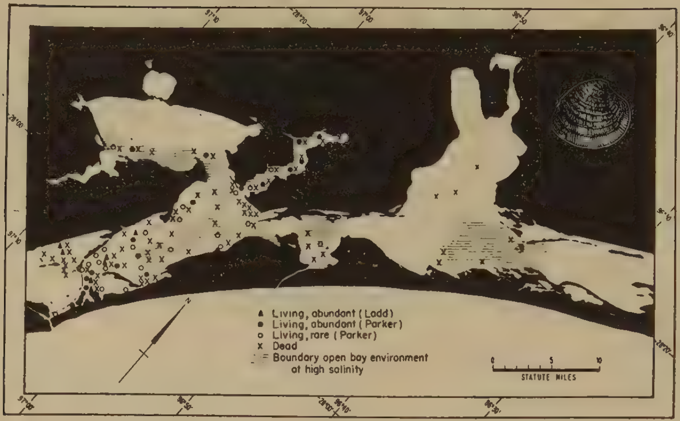

Living, abundant (Ladd)
Living, abundant (Parker)
Living, rare (Parker)
Dead
Boundary open bay environment at high salinity
0 5 10
STATUTE MILES

FIG. 16a.—Distribution of pelecypod, *Chione cancellata*. Most abundant during times of high salinity, when it is found throughout lower bays and inlets.

reefs are figured on Plate I. All of the organisms found in the enclosed bay assemblages are given in Table II in the Appendix.

III. *Open high-salinity bays and sounds.*—The areal boundaries of the high-salinity bay assemblage correspond roughly to Ladd's "polyhaline facies" boundary in Aransas Bay. This assemblage also occupies a part of lower San Antonio Bay during times of extended high salinity. Many more species and numbers of individuals inhabit high-salinity bays during extended periods of lower and unstable salinities. Figures 16a and 16b illustrate the extent of the high-salinity bay

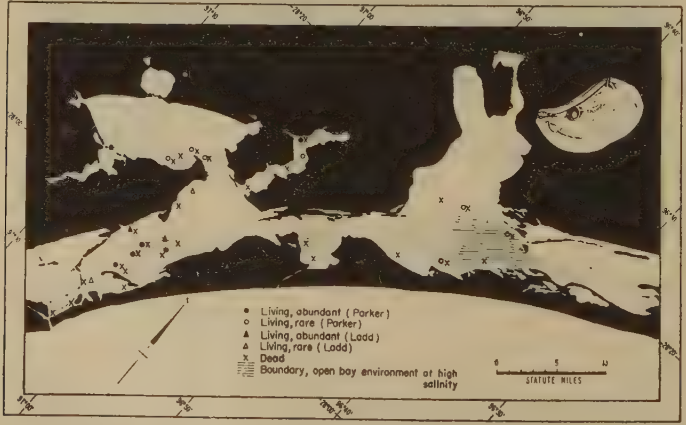

Living, abundant (Parker)
Living, rare (Parker)
Living, abundant (Ladd)
Living, rare (Ladd)
Dead
Boundary, open bay environment at high salinity
0 5 10
STATUTE MILES

FIG. 16b.—Distribution of pelecypod, *Pandora trilineata*, most abundant at times of high salinity.

environment in the Rockport area at times of extended high salinity, indicated by the superimposed distribution of two of the more characteristic invertebrates, the pelecypods, *Chione cancellata* and *Pandora trilineata*. The change in distribution of high-salinity organisms from a period of low salinity (Ladd) to the period covered by the present study is evident from Figures 16a and 16b. During Ladd's study both *Pandora* and *Chione* were confined to the inlet end of Aransas Bay, but by 1957 both occurred throughout Aransas, Copano, St. Charles, Mesquite, and lower San Antonio bays. From Ladd's study it was also deduced that the present invasion of these organisms into other parts of the bay system is unique, since Ladd found no dead shell of these species in the other bays.

In older deposits the presence of these forms in a thick section would indicate rather permanent open bay or sound conditions of near normal marine salinities. Their presence as either a thin layer or sparsely mixed with an enclosed-bay fauna, would indicate a brief change in salinity characteristics due either to a short-term change in climate (such as the recent drought), or a temporary enlargement of the inlets by storms.

Of the 34 invertebrate species taken alive in the high-salinity region, 17 species were abundant but not everywhere confined to the bays, and 8 species were confined to this environment. Although many invertebrate species are found in the open high-salinity bays and sounds, this environment may be the most difficult to identify in older deposits on the basis of the macrofauna, because the majority of forms are also found in the shallow shelf waters of the Gulf of Mexico. The high-salinity bays, therefore, are similar to the upper sound environment of the Mississippi Delta region (Parker, 1956). There is also considerable contamination of invertebrate species from the inter-reef and oyster-reef assemblages during times of extended low salinity, as can be seen by examining the distribution maps of the dead shell of characteristic species of the other environments. There are 8 reliable indicators for high-salinity bays under all conditions. These species are seldom found in the other bay environments (except inlets), and are rare on the continental shelf. The 8 species are here listed.

GASTROPODS
Nassarius acutus (Say, 1822)

PELECYPODS
Chione cancellata (Linné, 1767)
Diplodonta punctata (Say, 1822)
Macoma constricta (Bruguiere, 1792)
Pandora trilineata Say, 1822
Semele proficua (Pulteney, 1799)
Tagelus divisus (Spengler, 1794)
Trachycardium muricatum (Linné, 1758)

High-salinity bay centers.—The high-salinity bay environment can be subdivided into two facies or sub-environments on the basis of differing faunal assemblages and physical factors: bay centers and bay margins. Because the bay centers are deeper, they contain finer sediments and are characterized by more stable salinities and temperatures than the shallower bay margins. Living individuals are relatively scarce in the bay centers because of the predominance of fine clayey sediments. It is noted, however, that most of the mollusk species living in these fine sediments are deposit feeders, well adapted for obtaining organic matter for food in an environment which would be detrimental to most filter feeders. The faunal composition of the Rockport Bay centers is similar to that of the "lower Breton Sound and pro-delta slope" environment of the Mississippi Delta (Parker, 1956, p. 321), and both areas have similar ranges of environmental factors. The invertebrates most common to high-salinity bay centers are listed.

GASTROPODS

Nassarius acutus (Say, 1822)
Retusa canaliculata (Say, 1827)

PELECYPODS

Abra aequalis (Say, 1822)
Anadara campechiensis (Gmelin, 1790)
Anadara transversa (Say, 1822)
Corbula contracta Say, 1822
Diplodonta punctata (Say, 1822)
Mulinia lateralis (Say, 1822)
Nuculana acuta (Conrad, 1834)
Nuculana concentrica (Say, 1824)
Pandora trilineata Say, 1822
Periploma fragile (Totten, 1835)

CEPHALOPODS

Loliguncula brevis (de Blainville, 1823)

All of the invertebrate species taken in the bay centers are listed in Table II (Appendix).

High-salinity bay margins.—The bay margins are characterized by sandy sediments, ranging from sand-silt-clay to almost pure fine sand, a direct contrast to the fine clayey sediments of the bay centers (Table I and Fig. 8). The action of both wave movement perpendicular to the shore and the general parallel movement of high-salinity water along the shores (Figs. 8 and 9) produce narrow bands of coarse-grained sediments parallel with the shore. As it is probable that the larvae of the high-salinity gulf invertebrates located in and close to the inlets are also transported close to and parallel with the shore, the circulation may be a primary factor in determining the composition of the bay margin fauna. Evidence to support this premise is offered in the high percentage of species common to both the Gulf and inlets found along the bay margins. Another factor which may influence the composition of the bay margin assemblage is the availability of land-derived organic matter from runoff.

The loosely compacted sediments characterizing the bay margins may also be "ideal" for the penetration just below the surface sediments by the large filter-feeding pelecypods (*Mercenaria* and *Cyrtopleura*) characteristic of this assemblage. Apparently, the fine silty clays of the bay centers will not support these large clams, and inhibit the suspension-feeding mechanisms of these species; whereas the fine, very well sorted sands adjacent to the shore are too dense for penetration.

The extent of this assemblage in the Rockport area, and the distributions of the two species which best characterize the environment, the pelecypods, *Mercenaria mercenaria campechiensis* and *Tagelus divisus*, are shown in Figures 17a and 17b. Seventeen of the species of invertebrates considered most indicative of

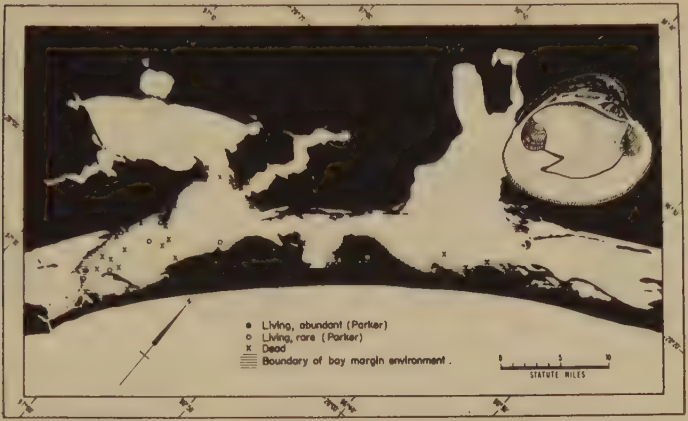

Living, abundant (Parker)
Living, rare (Parker)
Dead
Boundary of bay margin environment.
0
5
10
STATUTE MILES

FIG. 17a.—Distribution of pelecypod, *Mercenaria mercenaria campechiensis*, one of large heavy forms typical of high-salinity bay margins.

this environment are here listed and all of the species taken are given in the Appendix. Most of the named species of high-salinity bay environments are illustrated on Plate II.

GASTROPODS

Nassarius vibex (Say, 1822)

Vermicularia fargoi (Olsson, 1951)

PELECYPODS

Aequipecten irradians amplicostatus (Dall, 1898)

Chione cancellata (Linné, 1767)

Cyclinella tenuis (Récluz, 1854)

Cyrtopleura costata (Linné, 1758)

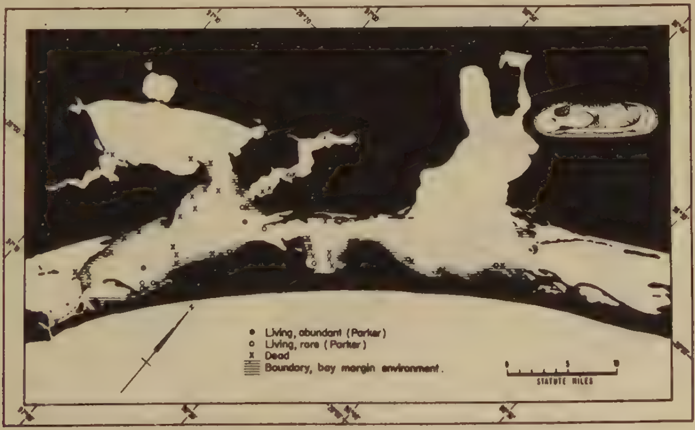
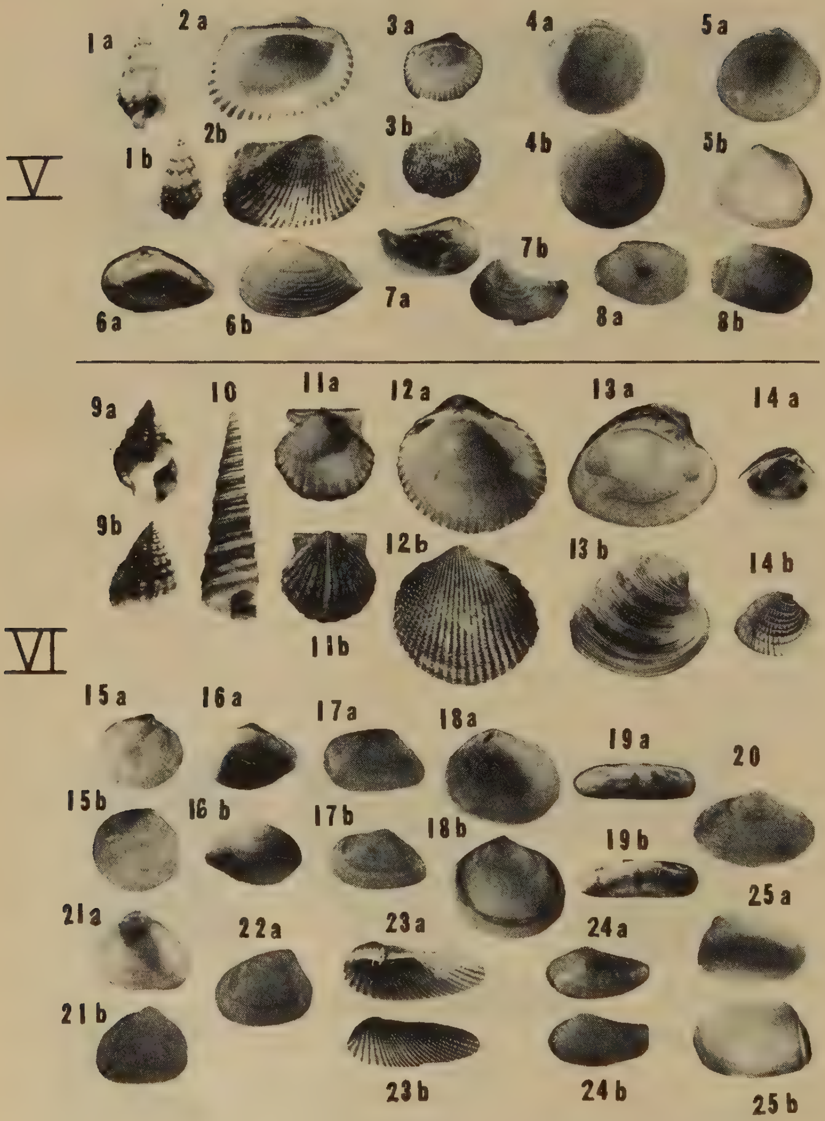

Living, abundant (Parker)
Living, rare (Parker)
Dead
Boundary, bay margin environment.
0
5
10
STATUTE MILES

FIG. 17b.—Distribution of pelecypod, *Tagelus divisus*, indicative of bay margins during high-salinity regimes.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3a
4a
5a
1b
2b
3b
4b
5b
6a
6b
7a
7b
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8b
VI
9a
10
11a
12a
13a
14a
9b
11b
12b
13b
14b
15a
16a
17a
18a
19a
20
15b
16b
17b
18b
19b
21a
22a
23a
24a
25a
21b
23b
24b
25b

Plate II

Ervillia concentrica (Gould, 1862)
Lyonsia floridana hyalina (Conrad, 1846)
Mercenaria mercenaria campechiensis (Dall, 1902)
Macoma brevifrons (Say, 1834)
Macoma constricta (Brugiere, 1792)
Mactra fragilis Gmelin, 1790
Mysella planulata (Stimpson, 1857)
Periploma inequale (C. B. Adams, 1842)
Tagelus divisus (Spengler, 1794)
Trachycardium muricatum (Linné, 1758)

ECHINODERMS

Thyone mexicana Deichmann, 1946

IV. *Inlets and inlet influence.*—The assemblage characterizing the inlet environment always occupies Aransas Pass and most of Lydia Ann Channel, even during the times of very reduced salinity in the Aransas Bay system. However, during times of drought and high salinity this assemblage invades Aransas Bay along the margins for a considerable distance, and follows the Intracoastal Waterway channel out into the bay (Fig. 18). The presence of a great many suspension-feeding inlet species adapted for holding fast to the bottom and requiring a constantly renewed source of plankton indicates that strong currents characteristic of this environment are important in determining the character of the assemblage. The Rockport inlet area also contains more species than any of the other bay environments. There is a mixture of species restricted to bays, shallow-shelf species, and certain forms indigenous to inlets. The inlets are the deepest part of the bay region (because of current scour), with depths of 16–22 feet as compared with the greatest depth of 12 feet in Aransas Bay. The greater depths and steady influx of Gulf water apparently minimize the short-term fluctuations of

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←«««

PLATE II

V. OPEN HIGH-SALINITY BAYS AND SOUNDS CENTERS

1. *Nassarius acutus*, size—11×4 mm., a. aperture, b. back.
2. *Anadara transversa*, size—15×10 mm., a. interior, b. exterior.
3. *Anadara campechiensis*, size—38×30 mm., a. interior, b. exterior.
4. *Diplodonta punctata*, size—12×11 mm , a. interior, b. exterior.
5. *Abra aequalis*, size—12×10 mm., a. interior, b. exterior.
6. *Corbula contracta*, size—7×5 mm., a. interior, b. exterior.
7. *Pandora trilineata*, size—20×11 mm., a. interior, b. exterior.
8. *Periploma fragile*, size—12×8 mm., a. interior, b. exterior.

VI. OPEN HIGH-SALINITY BAYS AND SOUNDS MARGINS

9. *Nassarius vibex*, size—12×8 mm., a. aperture, b. back.
10. *Vermicularia fargoi*, size—26×7 mm., aperture.
11. *Aequipecten irradians amplicostatus*, size—32×31 mm., a. interior, b. exterior.
12. *Trachycardium muricatum*, size—44×42 mm., a. interior, b. exterior.
13. *Mercenaria mercenaria campechiensis*, size—102×94 mm., a. interior, b. exterior.
14. *Chione cancellata*, size—26×22 mm., a. interior, b. exterior.
15. *Cyclinella tenuis*, size—15×15 mm., a. interior, b. exterior.
16. *Macoma constricta*, size—59×41 mm., a. interior, b. exterior.
17. *Macoma brevifrons*, size—12×7 mm., a. interior, b. exterior.
18. *Semele proficua*, size—13×11 mm., a. interior, b. exterior.
19. *Tagelus divisus*, size—29×9 mm., a. interior, b. exterior.
20. *Mactra fragilis*, size—35×22 mm., exterior.
21. *Mysella planulata*, size—4×3 mm., a. interior, b. exterior.
22. *Ervillia concentrica*, size—3×2 mm., interior.
23. *Cyrtopleura costata*, size—98×39 mm., a. interior, b. exterior.
24. *Lyonsia floridana hyalina*, size—12×5 mm., a. interior, b. exterior.
25. *Periploma inequale*, size—17×11 mm., a. interior, b. exterior.

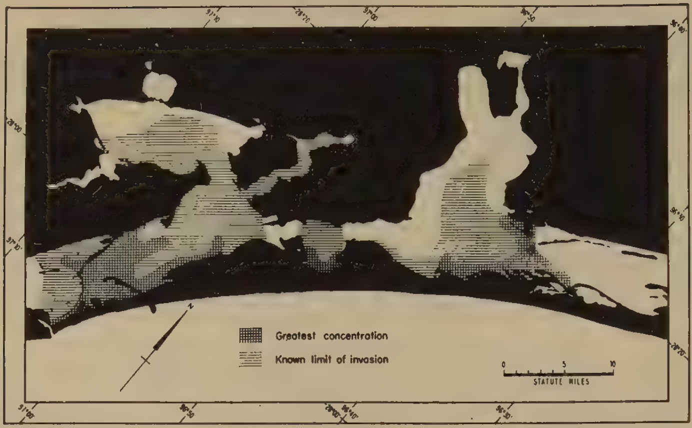

Fig. 18.—Limit of encroachment of high-salinity shallow shelf invertebrates into Rockport bays during period of extended high salinity.

air temperature and salinity, providing a more uniform marine environment. The range of physical factors characterizing this environment is given in Table I, and the complete list of animals taken in the inlets is given in Table II (Appendix).

The areal extent of the inlet environment is shown in Figures 19a and 19b, utilizing the distributions of the scaphopod, *Dentalium texasianum* and the solitary coral, *Astrangia astreiformis*. Although both of these invertebrates were taken alive only in the inlets or in the inlet-influenced regions, the distribution of dead individuals was quite different. *Astrangia* was completely confined to the lower end of Aransas Bay, living or dead, whereas *Dentalium*, although taken alive only in the inlet areas, was taken dead throughout Aransas Bay and San Antonio Bay. The fauna which can be considered indigenous to the inlets is here listed, and most of the species are illustrated on Plate III.

GASTROPODS

Anachis avara similis (Ravenel, 1861)
Cantharus tinctus (Conrad, 1846)
Epitonium angulatum (Say, 1830)
Epitonium humphreysi (Kiener, 1838)
Sinum perspectivum (Say, 1831)
Turbonilla interrupta Totten, 1835

SCAPHOPODS

Dentalium texasianum Philippi, 1849

PELECYPODS

Atrina seminuda (Lamarck, 1819)
Crassinella lunulata (Conrad, 1834)
Lucina amiantus (Dall, 1901)
Lucina crenella (Dall, 1901)
Tellidora cristata (Récluz, 1842)

CHITONS

Chaetopleura apiculata Say, 1830

ECHINODERMS

Arbacia punctulata (Lamarck, 1816)
Hemipholas elongata (Say, 1825)
Ophiolepis elegans Lütken, 1859
Ophiothrix angulatus (Say, 1825)

CORALS

Astrangia astreiformis Milne-Edwards and Haime, 1849

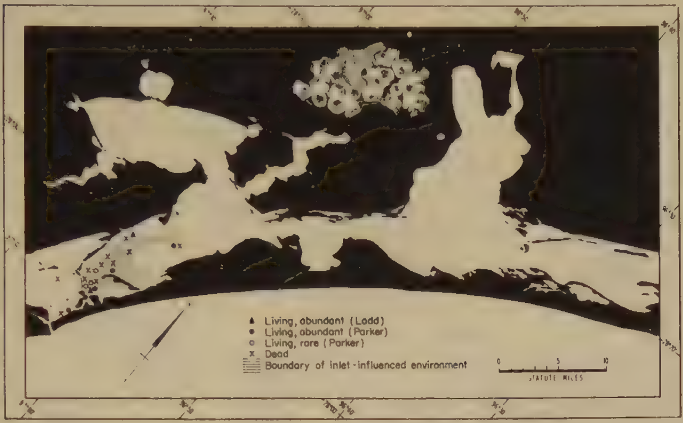
Living, abundant (Ladd)
Living, abundant (Parker)
Living, rare (Parker)
Dead
Boundary of inlet-influenced environment
0
5
10
STATUTE MILES

FIG. 19a.—Distribution of solitary coral, *Astrangia astreiformis*, indicative of inlet conditions or deep channels at high salinity.

CRUSTACEANS

Dromidia antillensis Stimpson, 1858

Heterocrypta granulata (Gibbes, 1849)

The following invertebrates which are abundant in the inlets, may also be found in large open marine sounds and the nearshore open Gulf of Mexico to depths of at least 30 feet; most of which are illustrated on Plate IV.

GASTROPODS

Busycon contrarium (Conrad, 1840)
Cantharus cancellarius (Conrad, 1846)

Crepidula fornicata (Linné, 1758)
Cyclostremiscus trilix (Bush, 1885)

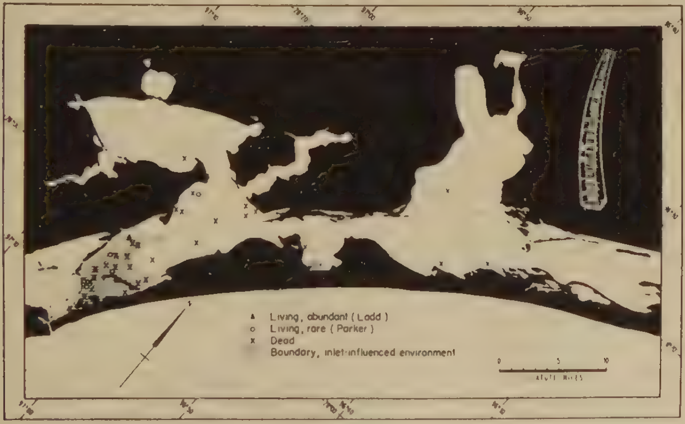
Living, abundant (Ladd)
Living, rare (Parker)
Dead
Boundary, inlet-influenced environment
0
5
10

FIG. 19b.—Distribution of scaphopod, *Dentalium texasianum*, characteristic of high-salinity channels or inlets.

Diodora cayenensis (Lamarck, 1822)
Neosimnia uniplicata (Sowerby, 1848)
Oliva sayana Ravenel, 1834
Olivella mutica (Say, 1822)
Natica pusilla Say, 1822
Polinices duplicatus (Say, 1822)
Pyramidella crenulata Holmes, 1859
Seila adamsi (H. C. Lea, 1846)
Thais haemastoma haysae Clench, 1927
Turbonilla incisa Bush, 1899

PELECYPODS

Corbula swiftiana C. B. Adams, 1852
Chione cancellata (Linné, 1767)
Eontia ponderosa (Say, 1822)
Macoma tenta (Say, 1834)
Petricola pholadiformis Lamarck, 1818
Tellina alternata Say, 1822
Tellina versicolor De Kay, 1843

COELENTERATES

Leptogorgia setacea (Pallas, 1766)
Renilla mülleri Kölliker

ECHINODERMS

Luidia alternata (Say, 1825)
Luidia clathrata (Say, 1825)
Mellita quinquiesperforata (Leske)

CRUSTACEANS

Hepatus epheliticus (Linné)
Libinia emarginata Leach
Ovalipes guadalupensis (Saussure)
Petrolisthes armatus (Gibbes)
Portunus gibbesi (Stimpson)
Portunus spinimanus Latreille
Portunus ventralis (Milne-Edwards)

The inlet environment may be difficult to recognize in older deposits, because of the large number of species common to both the nearshore shelf and bays. There are also many motile forms, such as gastropods, echinoderms, and crustaceans. This environment may be recognized in older deposits by the mixture of assemblages, many motile forms and the presence of the few indigenous attaching species.

Shallow, grassy, hypersaline lagoons and bays.—This environment is associated with the inlets which furnish a source of high-salinity water. The best example can be observed in Redfish Bay, and similar examples exist near the former Corpus Christi Pass at the northern end of the Laguna Madre, the shallow grassy bays near the entrance to the Gulf at Brazos Santiago Pass, and the shallow bay areas in Espiritu Santo Bay near Pass Cavallo (Fig. 1). The shallowness of these areas may be related to the influx of sand and other coarse materia

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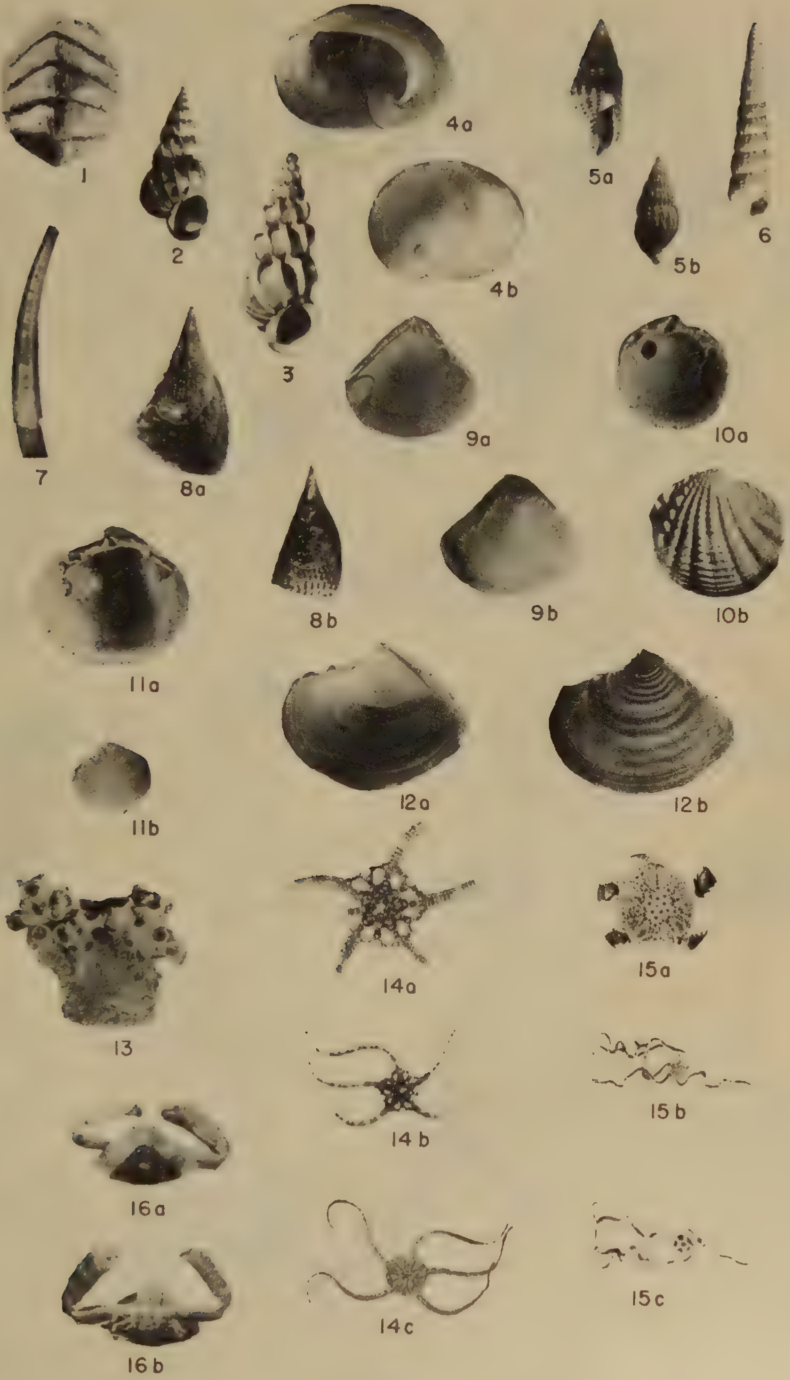
PLATE III

VII. INLET INFLUENCE (RESTRICTIVE)

1. *Chaetopleura apiculata*, size—10×7 mm., exterior.
2. *Epitonium humphryesi*, size—11×5 mm., aperture.
3. *Epitonium angulatum*, size—13×6 mm., aperture.
4. *Sinum perspectivum*, size—31×31 mm., a. aperture, b. top.
5. *Anachis avara similis*, size—8×3 mm., a. aperture, b. back.
6. *Turbonilla interrupta*, size—5×1 mm., aperture.
7. *Dentalium texasianum*, size—20 mm., side view.
8. *Atrina seminuda*, size—188×108 mm., a. interior, b. exterior.
9. *Crassinella lunulata*, size—8×7 mm., a. interior, b. exterior.
10. *Lucina amiantus*, size—6×6 mm., a. interior, b. exterior.
11. *Lucina multilineata*, size—5×5 mm., a. interior, b. exterior.
12. *Tellidora cristata*, size—15×13 mm., a. interior, b. exterior.
13. *Astrangia astreiformis*, size—25 mm., clump.
14. *Ophiolepis elegans*, size—disc—20 mm., arms, 55 m., a. disc, b. dorsal, c. ventral
15. *Hemipholis elongata*, size—disc—7 mm., a disc, b. dorsal, c. ventral.
16. *Heterocrypta granulata*, size—15×10 mm., a. dorsal, b. ventral.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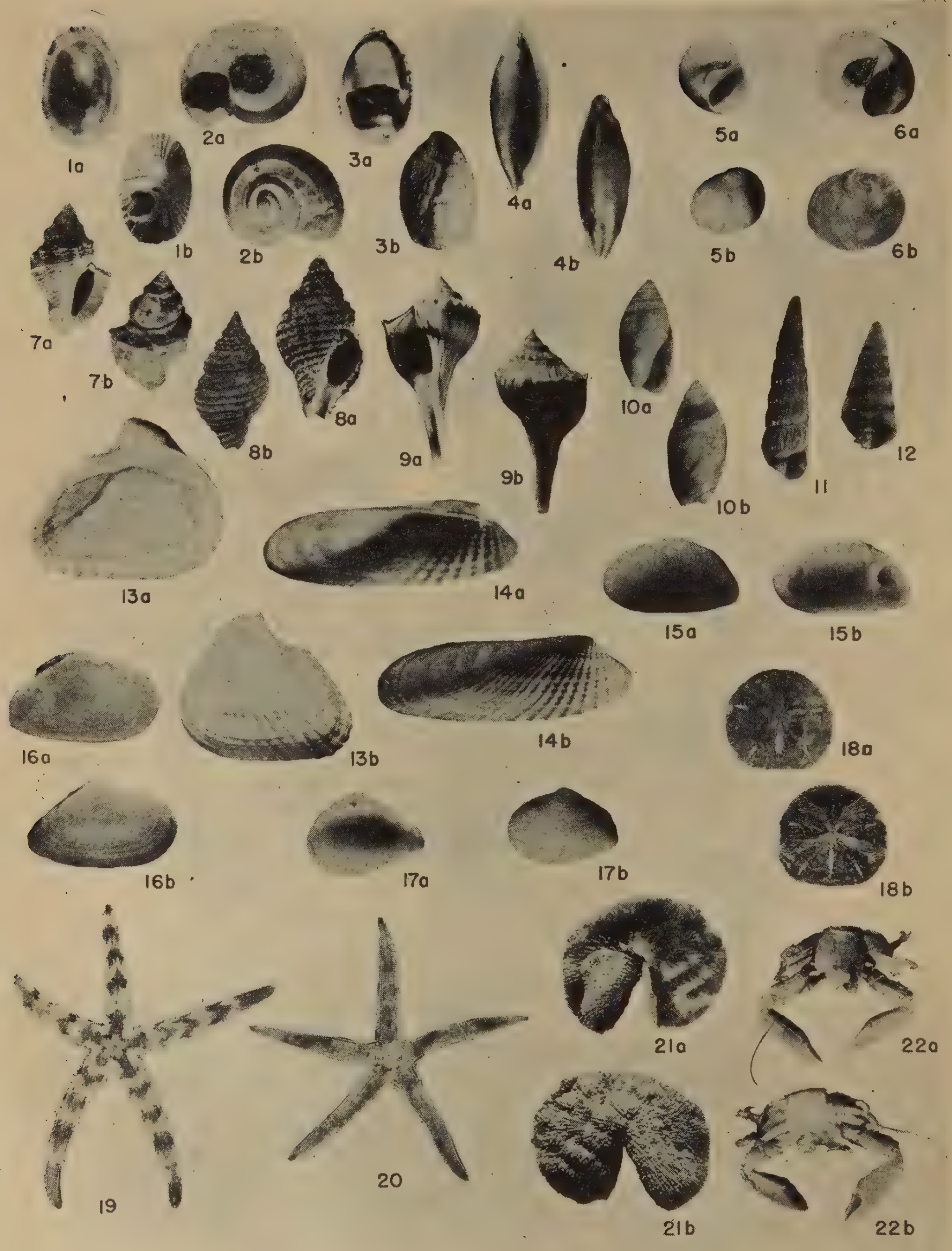
VII

PLATE III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21a
21b
22a
22b

VIII

PLATE IV

from the inlets in the form of tidal deltas. The physical characteristics of this environment in the Rockport region are tabulated in Table I. The hypersaline conditions are also typical of most of the Laguna Madre, but its isolation from a constant source of Gulf water results in only a few species living there, compared with the many species found in such areas as Redfish Bay.

The abundant rooted grasses and benthic algae associated with this environment support a large population of gastropods which either feed on or live upon the plants, as well as the many species which feed on decomposed plant material. These gastropods are excellent indicator species for this environment, because they are comparatively rare in most of the other depositional environments studied. Figure 20 shows the areal extent of the hypersaline shallow-bay environment in the Rockport region as illustrated by the distribution of the gastropod *Cerithium variabile*. This species is extremely abundant in the hypersaline shallow bays, although they occur intermittently in the other bays, in very shallow water close to shore, where salinities are usually much higher than in the rest of the bay (because of excess evaporation), and most of the bottom vegetation occurs. All of the species of invertebrates taken in this environment are listed in the Appendix, and the most abundant and characteristic species are listed here and illustrated on Plates V and VI.

GASTROPODS

Bittium varium (Pfeiffer, 1840)
Bulla striata Bruguière, 1792
Caecum nitidum Stimpson, 1851
Caecum pulchellum Stimpson, 1851
Cerithidea pliculosa (Menke, 1829)
Cerithium variable (C. B. Adams, 1848)
Crepidula glauca convexa Say, 1822
Haminoea succinea (Conrad, 1846)
Littorina irrorata (Say, 1822)
Melampus bidentatus Say, 1822
Modulus modulus (Linné, 1758)
Neritina virginea (Linné, 1758)
Niso interrupta Sowerby, 1834
Rissoina chesneli (Michaud, 1832)
Tegula fasciata (Born, 1780)
Truncatella pulchella Pfeiffer, 1839
Vermicularia fargoi Olsson, 1951

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PLATE IV

VIII. INLET INFLUENCE (NON-RESTRICTIVE)

1. *Diodora cayenensis*, size—12×7 mm., a. interior, b. exterior.
2. *Cyclostremiscus trilix*, size—2 mm. diameter, a. aperture, b. top.
3. *Crepidula fornicata*, size—23×14 mm., a. interior, b. exterior.
4. *Neosimnia uniplicata*, size—6×3 mm., a. aperture, b. back.
5. *Natica pusilla*, size, 3×4 mm., a. aperture, b. back.
6. *Polinices duplicatus*, size—41×39 mm., a. aperture, b. back.
7. *Thais haemastoma haysae*, size—59×33 mm., a. aperture, b. back.
8. *Cantharus cancellarius*, size—30×17 mm., a. aperture, b. back.
9. *Busycon contrarium*, size—80×39 mm., a. aperture, b. back.
10. *Olivella mutica*, size—8×2 mm., a. aperture, b. back.
11. *Turbonilla incisa*, size—5×1 mm., aperture.
12. *Pyramidella crenulata*, size—5×2 mm., aperture.
13. *Eontia ponderosa*, size—32×28 mm., a. interior, b. exterior.
14. *Petricola pholadiformis*, size—23×8 mm., a. interior, b. exterior.
15. *Tellina versicolor*, size—12×6 mm., a. exterior, b. interior.
16. *Tellina alternata*, size—52×29 mm., a. interior, b. exterior.
17. *Corbula swiftiana*, size—6×4 mm., a. interior, b. exterior.
18. *Mellita quinquiesperforata*—size—53×46 mm., a. dorsal, b. ventral.
19. *Luidia alternata*, size—130×120 mm., dorsal.
20. *Luidia clathrata*, size—95 mm., dorsal.
21. *Renilla mülleri*, size—75×58 mm., a. ventral, b. dorsal.
22. *Petrolisthes armatus*, size—12×10 mm., a. dorsal, b. ventral.

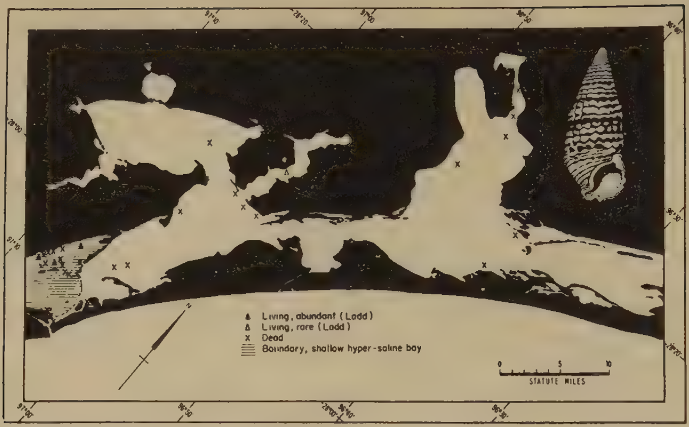
▲ Living, abundant (Ladd)
△ Living, rare (Ladd)
x Dead
▤ Boundary, shallow hyper-saline bay
0 5 10
STATUTE MILES
N

FIG. 20.—Distribution of gastropod, *Cerithium variabile*, indicative of shallow high-salinity and hypersaline bays and bay margins wherever benthic vegetation is abundant.

PELECYPODS

Amygdalum papyria (Conrad, 1846)
Anodontia alba Link, 1807
Anomalocardia cuneimeris (Conrad, 1846)
Brachidontes citrinus (Röding, 1798)
Cardita floridana (Conrad, 1838)
Laevicardium mortoni (Conrad, 1831)
Phacoides pectinatus (Gmelin, 1790)
Pseudocyrena floridana (Conrad, 1846)
Semele purpurescens (Gmelin, 1790)

The hypersaline bays have a larger standing crop (living populations at any one time) than any of the other bay environments, and at times the bottom is completely covered with living mollusks. The reasons for this high benthic productivity are not entirely evident, but they are surely related to abundance of marine

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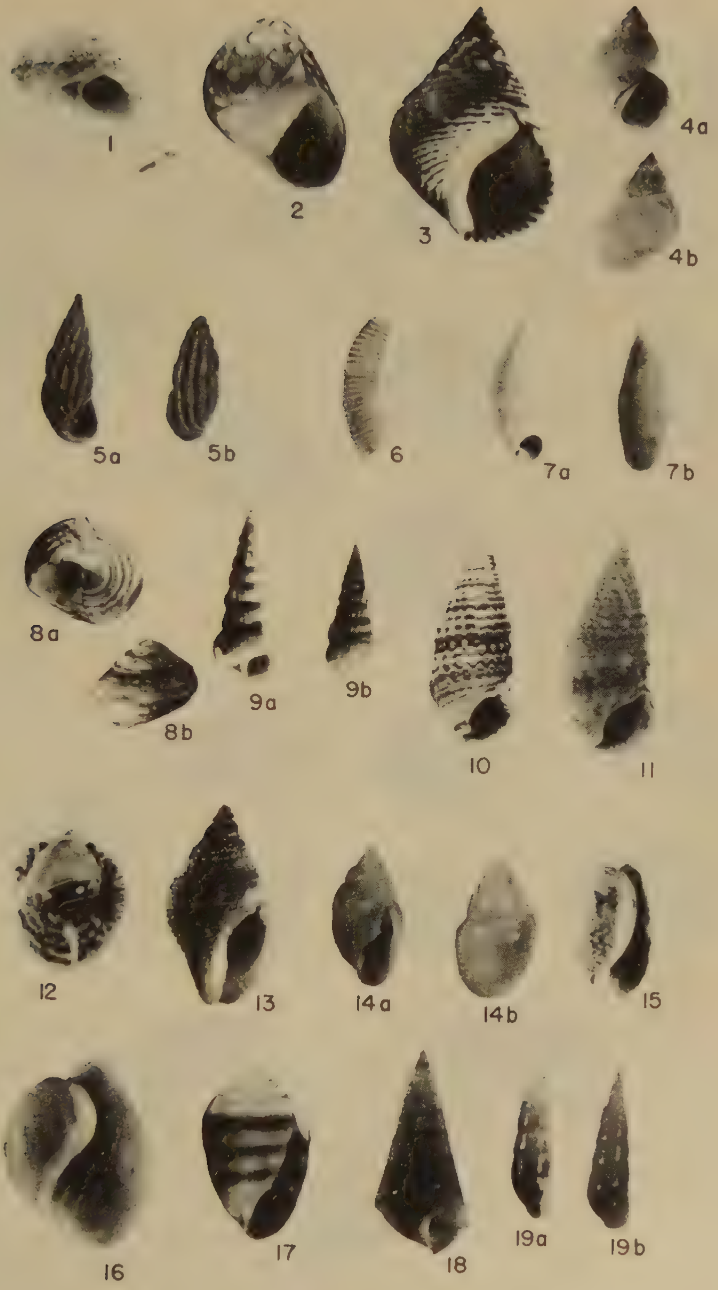
PLATE V

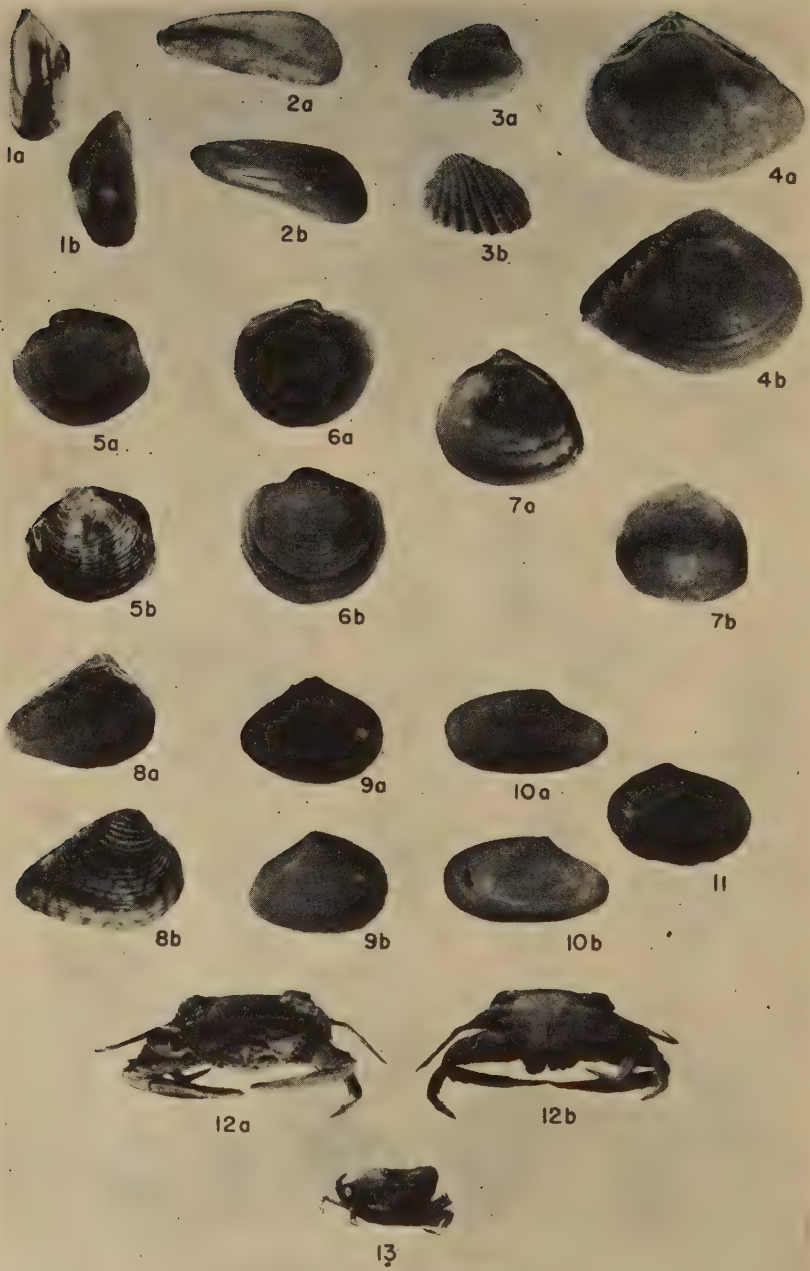
IX. SHALLOW, GRASSY, HYPERSALINE BAY AND LAGUNA MADRE
GASTROPODS

1. *Tegula fasciata*, size—11×8 mm., aperture.
2. *Neritina virginea*, size—11×10 mm., aperture.
3. *Littorina irrorata*, size—19×14 mm., aperture.
4. *Littorina nebulosa*, size—14×9 mm., a. aperture, b. back.
5. *Rissoina chesneli*, size—4×1 mm., a. aperture, b. back.
6. *Caecum pulchellum*, size—3×1 mm., side view.
7. *Caecum nitidum*, size—3×1 mm., a. aperture, b. back.
8. *Modulus modulus*, size—9×10 mm., a. aperture, b. back.
9. *Cerithidea pliculosa*, size—32×11 mm., a. aperture, b. back.
10. *Cerithium variabile*, size—12×5 mm., aperture.
11. *Cerithium*, species (juvenile), size—5×2 mm., aperture.
12. *Crepidula glauca convexa*, size—17×10 mm., aperture.
13. *Cantharus tinctus*, size—21×14 mm., aperture.
14. *Acteon punctostriatus*, size—5×2 mm., a. aperture, b. back.
15. *Bulla striata*, size—15×8 mm., aperture.
16. *Haminoea succinea*, size—12×9 mm., aperture.
17. *Melampus bidentatus*, size—11×7 mm., aperture.
18. *Niso interrupta*, size—5×2 mm., aperture.
19. *Odostomia bisuturalis*, size—5×1 mm., a. half aperture, b. aperture.


1
2
3
4a
4b
5a
5b
6
7a
7b
8a
8b
9a
9b
10
11
12
13
14a
14b
15
16
17
18
19a
19b

IX

Plate V


1a
2a
3a
4a
1b
2b
3b
4b
5a
6a
7a
5b
6b
7b
8a
9a
10a
11
8b
9b
10b
12a
12b
13

IX

Plate VI

vegetation. It is suspected that the warmer, shallow, and more transparent (because they are more protected and calmer) saline waters are nearly ideal for the photosynthetic production of plant material. This material provides food for algae feeders, a place of attachment for many sessile gastropods and pelecypods (*Crepidula*, *Brachidontes*, and *Amygdalum*), and a source of organic material on the bottom for the detritus feeders. With this increase in available organic material, there appears to be a corresponding increase in zooplankton which furnishes an abundant food source for the filter feeders.

ASSEMBLAGES OF LAGUNA MADRE

The Laguna Madre is a region with environmental characteristics similar to those of the shallow hypersaline lagoon and bays of the Rockport region previously discussed. This long narrow lagoon stituated between Corpus Christi and the Mexican Border (Figs. 21a and 21b and Fig. 1) is separated from the Gulf of Mexico along all of its 130-mile length by Padre Island, a barrier mostly less than a mile wide with no inlets to the Gulf of Mexico except at the extreme southern end, the Brazos Santiago Pass. The Laguna Madre is characterized by predominantly sand and shell sediments, extreme shallowness (from tidal flats to 10 feet), and by year-round hypersalinities. Before the construction of the Intracoastal Waterway, monthly averages of salinity ranged from $50^\circ/_{oo}$ to more than $100^\circ/_{oo}$ (Collier and Hedgpeth, 1950, p. 162). Recently, slightly lower salinities, with a high of $80^\circ/_{oo}$ were reported by Simmons (1957, p. 167). Although salinity values higher than that of normal sea water ($35^\circ/_{oo}$) have been recorded in other Texas bays for extended periods, hypersalinities are generally considered abnormal elsewhere along the northern Gulf coast. Detailed discussions of the variations in salinity and temperature in the Laguna Madre can be found in Hedgpeth (1947), Collier and Hedgpeth (1950), Breuer (1957), and Simmons (1957). A more detailed description of the hydrography and geology of the entire Laguna Madre can be found in Rusnak (in press).

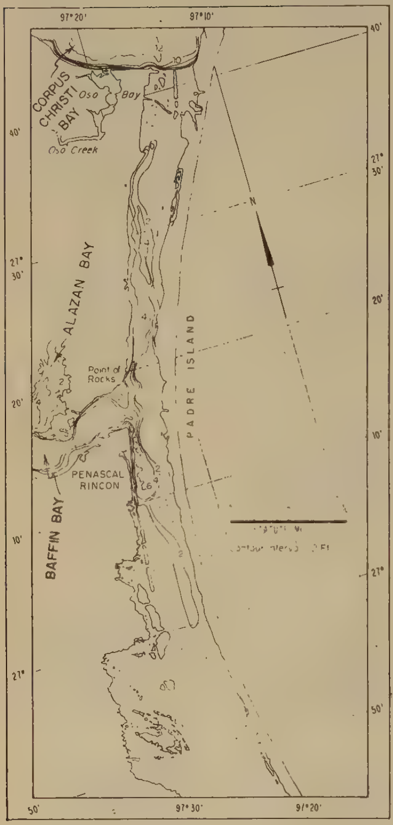
The very high salinities and high summer water temperatures (30°–35°C.),

←«««

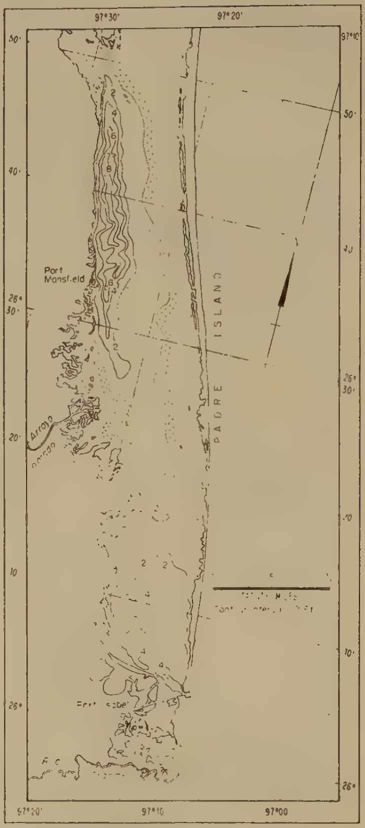
PLATE VI

IX. SHALLOW, GRASSY, HYPERSALINE BAY AND LAGUNA MADRE
PELECYPODS AND CRUSTACEANS

1. *Brachidontes citrinus*, size—18×9 mm., a. interior, b. exterior.
2. *Amygdalum papyria*, size—23×9 mm., a. interior, b. exterior.
3. *Cardita floridana*, size—15×10 mm., a. interior, b. exterior.
4. *Pseudocyrena floridana*, size—18×13 mm., a. interior, b. exterior.
5. *Phacoides pectinatus*, size—30×27 mm., a. interior, b. exterior.
6. *Anodontia alba*, size—65×60 mm., a. interior, b. exterior.
7. *Laevicardium mortoni*, size—15×14 mm., a. interior, b. exterior.
8. *Anomalocardia cuneimeris*, size—11×7 mm., a. interior, b. exterior.
9. *Tellina tampaensis*, size—10×5 mm., a. interior, b. exterior.
10. *Macoma tenta*, size—10×9 mm., a. interior, b. exterior.
11. *Semele purpurescens*, size 19×13 mm., interior.
12. *Portunus gibbesi*, size—49×22 mm., a. dorsal, b. ventral.
13. *Neopenope texana sayi*, size 8×7 mm., side or ventral view.


97°20'
97°10'
40'
CORPUS CHRISTI BAY
Oso Bay
Oso Creek
21° 30'
20'
10'
21°
50'
ALAZAN BAY
Point of Rocks
PENASCAL RINCON
BAFFIN BAY
PADRE ISLAND
N
97°30'
97°20'

21a


97°30'
97°20'
97°10'
50'
40'
Port Mansfield
26° 30'
20'
10'
26°
Arroyo
PADRE ISLAND
57°20'
97°10'
97°00

21b

FIG. 21a.—Bathymetry and locality names of northern Laguna Madre (after Rusnak, in press, preliminary map).

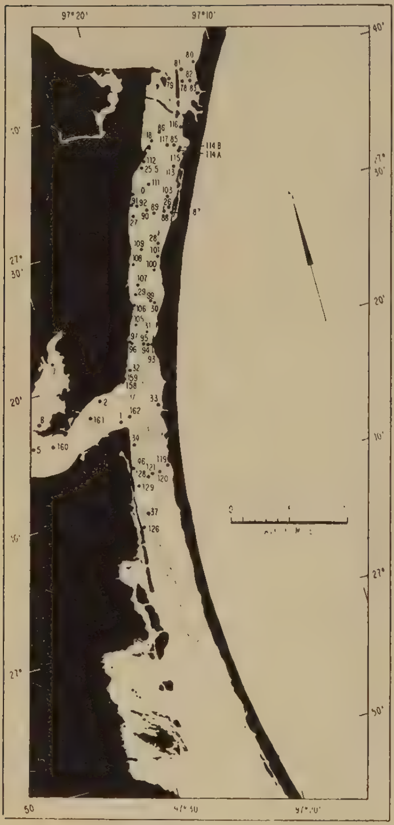
FIG. 21b.—Bathymetry and locality names of southern Laguna Madre (after Rusnak, in press, preliminary map).

and the absence of exchange of water between the Laguna Madre and either the Gulf of Mexico or Corpus Christi Bay create a physiographic and biological environment distinct from those in other Texas bays (except for Redfish Bay). The range of physical variables for the various parts of the Laguna Madre can be found in Table I.

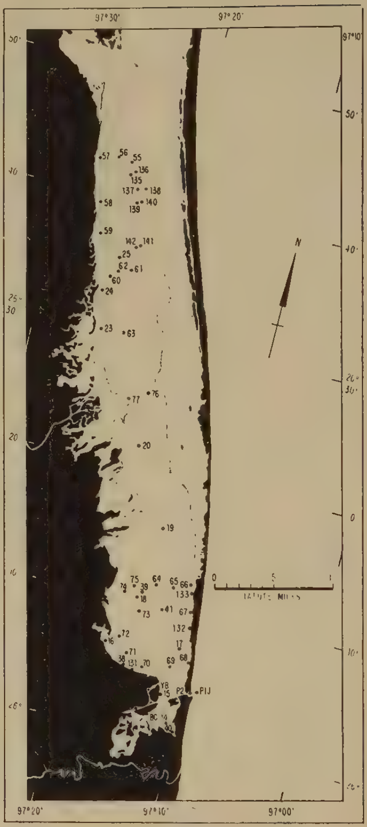
The Laguna Madre is of special interest, since it appears to be one of the most biologically productive areas in the world (Hedgpeth, 1947, 1958, pp. 716–17; and Simmons, 1957). Although the production of fish is two to three times greater in the Laguna Madre than the entire production of all other Texas bays, vertebrates are not the only organisms which are extremely abundant. Counts of 1,400–2,000 specimens per square foot of living individuals of the pelecypod, *Anomalocardia cuneimeris*, were made in the northern Laguna (Simmons, 1957, pp. 180, 192). The amount of attached bottom vegetation in some parts of the Laguna is also many times greater than that found in other Gulf coastal bays. Phytoplankton productivity may be very high, although only one productivity measurement has been made (by Simmons and W. H. Thomas for A.P.I. Project 51). A value of 908 micrograms of carbon fixed/liter/day was obtained in the northern Laguna, as compared with 350 micrograms of carbon fixed/liter/day for Breton Sound in the Mississippi Delta region, and 2–6 micrograms of carbon fixed/liter/day in the open Gulf of Mexico (Simmons and Thomas, personal communication). Populations of zooplankton (primarily copepods) are extremely high throughout the year. Simmons (1957, p. 177) reports counts of the copepod, *Acartia tonsa* Dana, of more than 7,000,000 individuals per liter. As in Redfish Bay at the north, the high productivity of planktonic organisms and benthic vegetation apparently contributes the organic matter needed to support the large population of mollusks which feed on detrital deposits.

From the analyses of the 121 biological stations (Figs. 22a and 22b) in the Laguna Madre, and from notes and specimens furnished by Mrs. Jeanne Frisbey of Port Isabel, Texas, it was possible to characterize five areas or environments (Fig. 23) based on the occurrences of 89 species of invertebrates. These five environments not only have distinct sediment and salinity characteristics, but also have distinctive faunal assemblages as well. Although the majority of invertebrate species taken in the Laguna Madre are also taken in smaller numbers in some of the other Texas bays and on the nearshore shelf of the Gulf of Mexico, a few species are apparently restricted to the Laguna. The assemblages characterizing four of these environments do not have exact counterparts elsewhere on the Gulf of Mexico coast, except possibly the Laguna Madre of Mexico (Hildebrand, 1958).

I. *Inlet-influenced, hypersaline lagoon.*—The extreme southern end of the Laguna Madre (Fig. 21b) may be described as an inlet-influenced, hypersaline environment, because it is strongly influenced by the flow of Gulf of Mexico water through the Brazos Santiago Pass. The presence of the inlet in this region permits an immigration of a considerable number of Gulf species into the Laguna, and in this respect the area closely resembles the inlets and shallow hypersaline bays near inlets farther north along the Texas coast. The distribution maps of two of the characteristic mollusks of the Laguna inlet-influenced environment (Figs. 24a and 24b), the gastropod, *Anachis avara semiplicata*, and the pelecypod, *Chinone cancellata*, demonstrate the boundaries of this assemblage. Although *Chione* is indicative of the inlet areas in the Laguna, and also of the margins of open high-salinity bays and sounds at the north, both regions have similar salinity and bottom sediment characteristics. Dead shell of *Chione* was taken in


97°20'
97°10'
40'
30'
20'
10'
27°
50'
114 B
114 A
160
161
162
129
126
37

22a


97°30'
97°20'
97°10'
97°00'
50'
40'
26°
N
PIJ
136
137
138
139
140
141
142
133
132
MILES

22b

FIG. 22a.—Biological station locations, northern Laguna Madre (mostly taken with minidredge).

FIG. 22b.—Biological station locations, southern Laguna Madre (mostly taken with minidredge).

the more hypersaline parts of the Laguna, but they have apparently been reworked from older deposits. Sixty-nine species of invertebrates were taken in this environment: 37 alive and 32 as dead shells, The more characteristic species are listed here, and the physical characteristics are given in Table I.

GASTROPODS

Anachis avara semiplicata (Stearns, 1873)
Bulla striata Bruguière, 1792
Crepidula glauca convexa Say, 1822
Littorina nebulosa (Lamarck, 1822)
Nassarius vibex (Say, 1822)
Neritina virginea (Linné, 1758)
Turbonilla interrupta Totten, 1835

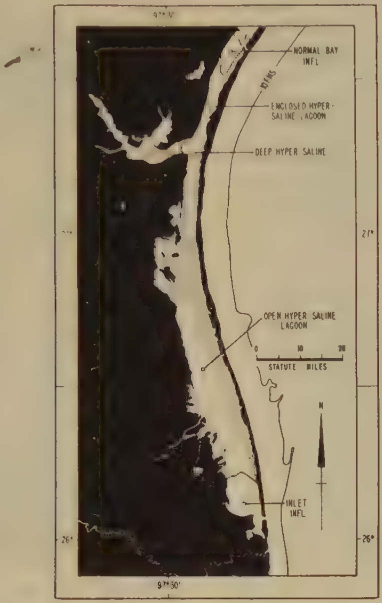


FIG. 23.—Areal distribution of macro-invertebrate assemblages in Laguna Madre.

PELECYPODS

Abra aequalis (Say, 1822)
Aequipecten irradians amplicostatus (Dall, 1898)
Anadara transversa (Say, 1822)
Anomia simplex d'Orbigny, 1842
Atrina seminuda (Lamarck, 1819)
Chione cancellata (Linné, 1767)
Cyrtopleura costata (Linné, 1758)
Macoma tenta (Say, 1834)
Nuculana acuta (Conrad, 1834)
Ostrea equestris (Say, 1834)

ECHINODERMS

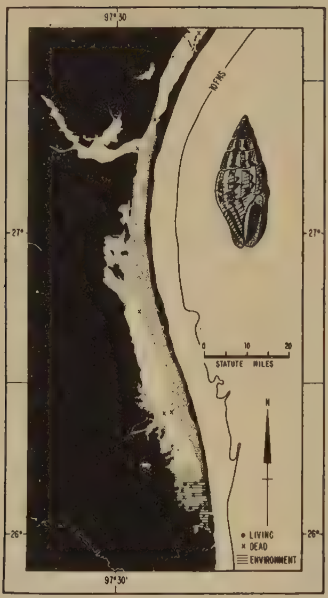
Lytechinus variegatus (Lamarck, 1816)
Ophiothrix angulatus (Say, 1825)

CRUSTACEANS

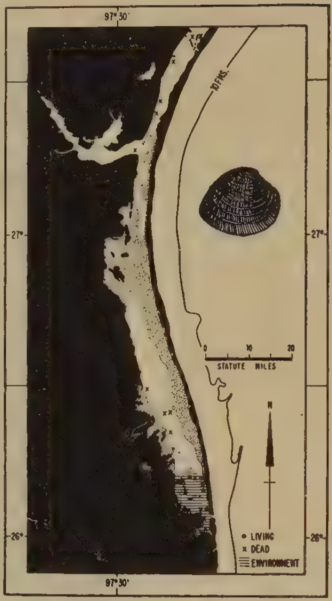
Crangon heterochelis (Say)
Neopenope texana sayi (Stimpson)
Portunus gibbesi (Stimpson)

This part of the lagoon, with normal marine conditions and comparatively stable physical conditions has by far the greatest diversity of species of invertebrates, although the observed number of individuals of each species is small. All of the species collected in this environment are given in Table II in the Appendix.

II. *Open shallow hypersaline lagoon.*—This environment (Fig. 23), adjacent to the inlet region and extending to the tidal flat and sand-dune region separating the southern and northern Laguna Madre, comprises the largest open-water area in the Laguna. The open hypersaline lagoon, like the shallow hypersaline lagoon near inlets, contains an abundance of marine vegetation, and this is one of the major factors influencing the composition of the assemblages. The ranges



24a



24b

FIG. 24a.—Distribution of gastropod, *Anachis avara semiplicata*, indicative of inlet-influenced hypersaline part of southern Laguna Madre.

FIG. 24b.—Distribution of pelecypod, *Chione cancellata*, indicative of inlet-influenced part of southern Laguna Madre and open bays on north.

of other physical factors characteristic of this environment are given in Table I. The distributions of two of the characteristic pelecypods, *Amygdalum papyria* and *Laevicardium mortoni*, are illustrated (Figs. 25a and 25b). The fact that *Amygdalum* occupies the western shore and *Laevicardium* lives primarily on the eastern shore can be partly explained by the abundance of vegetation on the western shore, utilized by *Amygdalum* for attachment, and the specific sediment types (Fig. 26) preferred by *Laevicardium* on the eastern side. The characteristic mollusks of this assemblage are here listed.

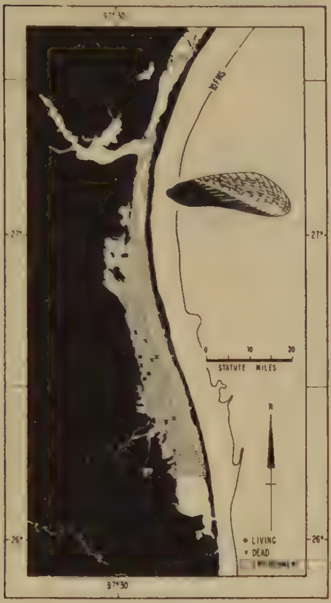
GASTROPODS

Bittium varium (Pfeiffer, 1840)
Haminoea succinea (Conrad, 1846)
Mitrella lunata (Say, 1826)
Truncatella pulchella Pfeiffer, 1839

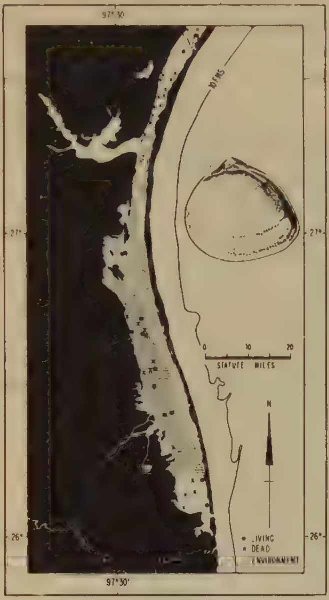
PELECYPODS

Amygdalum papyria (Conrad, 1846)
Brachidontes citrinus (Röding, 1798)
Laevicardium mortoni (Conrad, 1830)
Macoma brevifrons (Say, 1834)
Mactra fragilis Gmelin, 1790
Pseudocyrena floridana (Conrad, 1846)
Tagelus divisus (Spengler, 1794)
Tellina tampaensis Conrad, 1866

In all, 33 species were collected in the open hypersaline environment: 13 alive and 20 as dead shells. All of the species collected in this region are given in



25a



25b

FIG. 25a.—Distribution of pelecypod, *Amygdalum papyria*, indicative of vegetation-covered, open hypersaline part of southern Laguna Madre.

FIG. 25b.—Distribution of pelecypod, *Laevicardium mortoni*, indicative of shallow sandy part of open hypersaline environment in Laguna Madre.

the Appendix. Although the open lagoon region is characterized by relatively stable conditions, these conditions are at the upper limit of tolerance for most of the species of marine invertebrates. The number of living species is therefore sharply reduced from the adjacent slightly variable but more favorable inlet-influenced environment. Although there were fewer species, the number of living individuals of each species was high.

III. *Enclosed hypersaline lagoon.*—As can be observed in Figure 21a, the shallow central part of the northern Laguna Madre is hydrographically and geographically separated from the rest of the Laguna by a land area on the south and a sill of slightly submerged rocks across Baffin Bay. A series of islands separates this region from Corpus Christi Bay. Physical data indicate that this environment is characterized by excessively high summer water temperatures and more or less stable hypersalinity, ranging from 40 to 79‰.

The species living in the enclosed lagoon are found in other bays on the Gulf coast, but not in such large numbers or in the association peculiar to this area. The distributions of two of the characteristic pelecypods, *Anomalocardia cunei-*

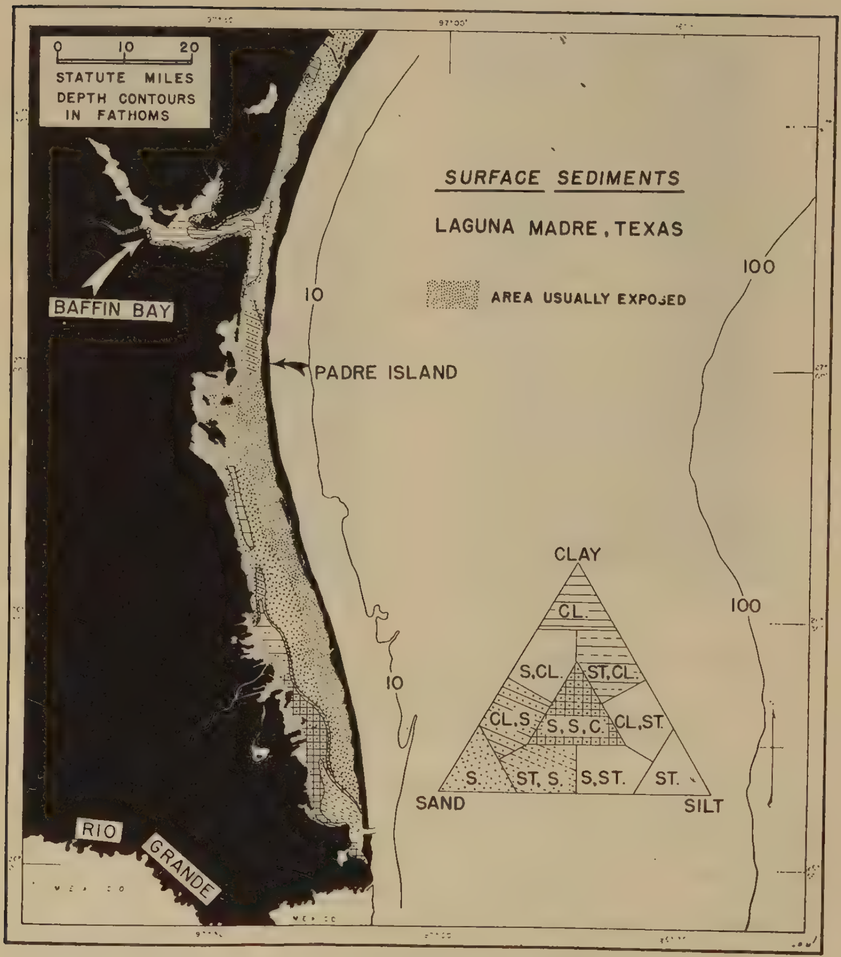
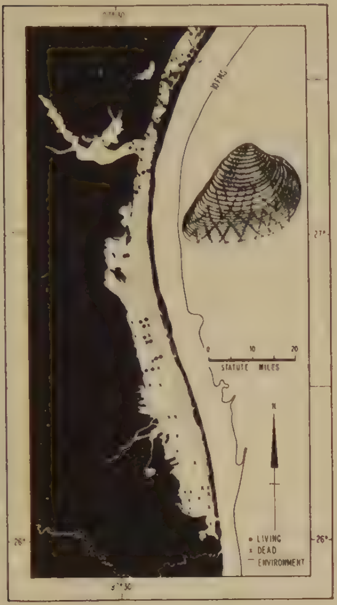
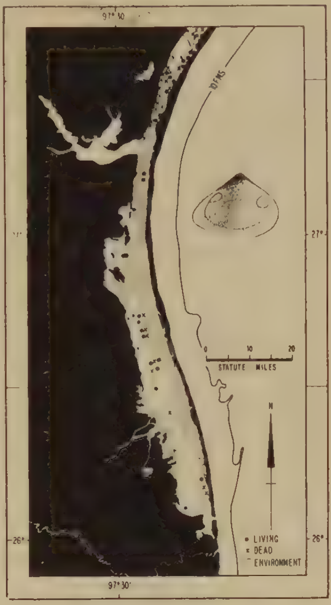

0 10 20
STATUTE MILES
DEPTH CONTOURS IN FATHOMS
SURFACE SEDIMENTS
LAGUNA MADRE, TEXAS
AREA USUALLY EXPOSED
97°00'
BAFFIN BAY
PADRE ISLAND
10
10
100
100
CLAY
CL.
S.CL.
ST.CL.
CL.S.
S.S.C.
CL.ST.
S.
ST.S.
S.ST.
ST.
SAND
SILT
RIO GRANDE

FIG. 26.—Distribution of surface sediments of Laguna Madre, based on percentages of sand-silt-clay (after Shepard and Rusnak, 1957).

meris and *Tellina tampaensis*, are shown in Figures 27a and 27b. The other two common mollusks are the gastropod, *Cerithium variabile*, and the pelecypod, *Mulinia lateralis*. All of the mollusks taken in the environment are given in the Appendix. Thirty-eight species of mollusks were collected in the enclosed lagoon, but only four were taken alive. The shells of the other species appear to be mostly reworked material from the dredge spoils of the Intracoastal Waterway and the



27a



27b

FIG. 27a.—Distribution of pelecypod, *Anomalocardia cuneimeris*, characteristic of enclosed hypersaline environment in Laguna Madre.

FIG. 27b.—Distribution of pelecypod, *Tellina tampaensis*, characteristic of very shallow portions of enclosed hypersaline environment, Laguna Madre.

Pleistocene-Recent deposits on the western shore (Rusnak, in press).

Virtually the same molluscan assemblage is reported from the Laguna Madre de Tamaulipas of Mexico by Hildebrand (1958). Hildebrand lists *Laevicardium mortoni*, *Anomalocardia cuneimeris*, and *Mulinia lateralis* as living in areas with a salinity range of from 38 to 49°/oo.

Although only four species of shelled invertebrates were taken alive in this environment, the living individuals of these species per sample outnumbered all of the other individuals in the rest of the Laguna Madre. This population (at certain times of the year) constitutes the largest assemblage of living mollusks, except for the oyster reefs, along the northern Gulf coast, despite the fact that this is an area of very adverse physical conditions in terms of high salinities and temperatures, as well as extreme shallowness. Although adverse, the physical conditions are more stable in salinity range (always hypersaline) than the other parts of the Laguna Madre, resulting in high populations of a very few species.

IV. *Deep hypersaline bay, clayey substrate.*—Baffin and Alazan bays (Figs. 21a and 23) form the boundaries of the relatively deep hypersaline bay area of the

Laguna Madre. The physical characteristics of these bays are discussed by Breuer (1957) and Rusnak (in press), and are listed in Table I. The outstanding characteristics of Baffin Bay are sediments composed of more than 75 per cent clay, extremely variable salinities, ranging from less than 2°/₀₀ during periods of high runoff to well over 80°/₀₀ during droughts; and depths considerably greater than the adjacent parts of the Laguna Madre.

Of the total of 90 invertebrate species found in the Laguna Madre, only 8 species were taken in the Baffin-Alazan region, and of these eight, only one was taken alive during this study, *Mulinia lateralis*. This species has been taken alive in every other environment on the Gulf coast except the outer continental shelf. Six species of pelecypods were taken as dead shells, and *Anomalocardia cuneimeris* has been found living in Baffin Bay, and at times has suffered mass mortalities during freezes and extremely high salinities (Breuer, 1957). Most of the pelecypods were found as shell associated with plant debris along the shore, and may have drifted in from the central part of the Laguna Madre. Some dead specimens of the gastropod, *Acteon punctostriatus*, were collected in adjacent waters during the present study, and this species was reported as living in Baffin Bay by Hedgpeth (1958, p. 716). Since this environment is the most variable and adverse for marine life, it was not surprising to find the smallest number of species, as well as the least number of individuals in the Laguna Madre.

Although this environment would be difficult to detect in ancient sediments on the basis of macrofauna alone, a definite clue would be suggested by the presence of *Mulinia lateralis*, or small mactrid-like pelecypods, in a very fine-grained shale. *Mulinia* is an excellent indicator of environmental adversity, thriving best in very low or very high salinities, where most marine invertebrates have difficulty surviving. It can also withstand rapid and extreme hydrographic changes in a very short time. This species ranges from the New England coast in the north to South America (Abbott, 1954), and occurs in the fossil record as far back as the late Miocene (Maury, 1920).

V. *Hypersaline lagoon, influenced by adjacent lower-salinity bay.*—The extreme northern end of the Laguna Madre adjacent to Corpus Christi Bay constitutes the area designated as the hypersaline lagoon modified by enclosed, low-salinity bay waters (Fig. 23). The range of physical factors in this region is intermediate between that of the enclosed hypersaline lagoon and that of a "normal," enclosed estuary or bay, exemplified by Corpus Christi Bay. The range of physical factors is given in Table I. Like the enclosed lagoon, the sediments are predominantly sand and shelly sand (Fig. 26), and the water depths are between 2 and 4 feet (Fig. 21a). The primary difference between this and the adjacent enclosed lagoon is the periodic influence of lower-salinity waters entering from Corpus Christi Bay, permitting intermittent invasion by normal bay fauna.

The fauna of this environment is a mixture of species found in greater abundance in the enclosed lagoon, and species usually associated with intermediate to high-salinity bays. The proximity of a former inlet, Corpus Christi Pass (Fig.

(664)

21a) is indicated by the presence of old echinoid fragments and shells of *Crassinella lunulata*, *Lucina amiantus*, and *Dentalium texasianum*, typical of the inlet assemblage. None of the species of living invertebrates taken is abundant and distinctive enough to characterize this environment, although the composition of the assemblage may be diagnostic in indicating a mixture of environments. Fifty-four species of invertebrates were collected in this region: of these only 11 species were taken alive. The large number of invertebrate species and small number of living individuals per species suggest a favorable environment for marine organisms, but one which is not quite as stable as the inlet areas. The abundant and more or less characteristic species forming this assemblage are here listed, and all of the species collected are given in Table II in the Appendix.

GASTROPODS
Nassarius vibex (Say, 1822)
Odostomia bisuturalis (Say, 1821)

PELECYPODS
Crassostrea virginica (Gmelin, 1791)
Ensis minor Dall, 1899
Mactra fragilis Gmelin, 1790
Phacoides pectinatus (Gmelin, 1790)
Tellina tampaensis Conrad, 1866

CRUSTACEANS
Callinectes sapidus Rathbun

Those few species taken in the Laguna Madre, and not shown in the Rockport faunal plates, are included on Plates V and VI.

Generalizations concerning Laguna Madre.—In summary, the study of faunal assemblages in the Laguna Madre, where there is a wide range of values of physical factors, and varying degrees of stability of these factors, has supported the contention that the variability and adversity of the environments are two very important factors which influence the composition of biological assemblages. This thesis has been stated in part in "Liebig's Law of Minimum," restated by Taylor (1934, p. 378) as: "The growth and functioning of an organism is dependent upon the amount of essential environmental factor presented to it in minimal quantity during the most critical year or years of the climatic cycle." With this thesis in mind, observations in the Laguna Madre support the following series of criteria which may be useful in stratigraphic interpretation.

1. Under conditions involving variable and extreme salinities and temperatures, only a few species of marine invertebrates and individuals of each species may survive.

2. When hydrographic conditions are stable, but salinities and temperatures are in the extreme range, a few tolerant species may become extremely abundant.

3. When physical conditions are stable and within the normal range for marine environments, there will be many species but fewer individuals per species.

The same situation was found in the Mississippi Delta region. As a rule, the farther one moves away from the Delta, where there are lowered salinities and high turbidity, the more species and fewer individuals of each species are found in any one sample (Parker, 1956, pp. 368–69).

INTERPRETATION OF POST-PLEISTOCENE DEPOSITIONAL HISTORY OF A TEXAS BAY

In the course of earlier geologic studies carried out by A.P.I. Project 51 in the Rockport area, deep borings were made in the Guadalupe River Delta, San Antonio Bay, and Matagorda Island. Some of these borings were re-examined in the light of macrofaunal interpretations alone. Except for one boring in the Delta and another in Matagorda Island, in which a Porter soil sampler was used, all of the borings used here were taken with a light rotary drilling rig having a 3-inch-diameter core barrel. Details of these operations and lithologic interpretations of the cores can be found in Shepard and Moore (1955) and Shepard (1956).

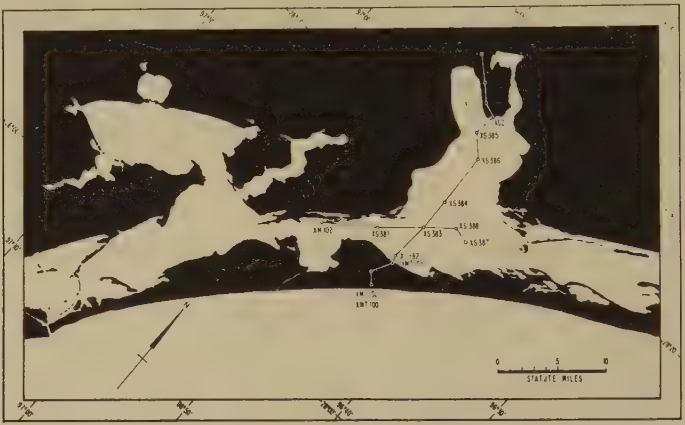


FIG. 28.—Location of core holes, used to interpret post-Pleistocene history of deposition in San Antonio and Mesquite bays.

Shortly after these borings had been obtained, all levels of the cores with macrofaunal remains were studied and the faunas listed as to species and comparative abundance. This information was incorporated with evidence supplied by the foraminiferal assemblages and analyses of sediment coarse fractions. Some of the shell and wood material from various levels in these borings was age-dated by the Carbon-14 method by Magnolia Petroleum Company's Field Research Laboratory. All of this information was then used to construct a possible late Pleistocene and Recent history of deposition in the Rockport bays, and the formation of the barrier islands.

In order to demonstrate the application of data obtained from macrofaunal analyses to the interpretation of older environment of deposition, the drillings from one traverse extending from the Guadalupe Delta to the Gulf and another parallel with the barrier islands and perpendicular to the previous traverse (Fig. 28) were re-examined. A cross section to a maximum depth of 90 feet was constructed, and the macrofaunal assemblages listed for each depth sampled

(Fig. 29). A new cross section was then made giving the probable gross environments of deposition (Fig. 30). Since the picture of environmental or morphological changes differed slightly from that published by Shepard and Moore (1955) for San Antonio Bay, a check of the original environmental interpretations by the Foraminifera Laboratory at Scripps Institution was made by Miss Frances L. Parker. This check revealed that both the microfauna and macrofauna were in good agreement as to environments of deposition in the present cross sections. The interpretations gained from the study of the perpendicular section across lower San Antonio Bay (Figs. 31a and 31b) also agreed with that obtained from the Guadalupe River to Gulf section.

If one examines the interpretations in the major cross section (Fig. 30), it can be seen that the estuarine deposits lie just above the Pleistocene (?) unconformity, and appear to be contained behind a topographic high at approximately the same position as the present barrier island. Since sea-level was about 70–120 feet lower, the Gulf shoreline would have been a considerable distance seaward of its present position, and San Antonio Bay could have been an embayed part of the upper part of a long estuary, similar to the present Calcasieu and Sabine lakes. There could also have been sufficient tidal influence to keep salinities high enough for oyster-reef growth. As sea-level rose, the shoreline moved in toward its present position, the narrow estuarine part was inundated, and for a brief period open sound with a strong nearshore Gulf influence existed in what is now lower San Antonio Bay. With the slowing of the sea-level rise to its present level, continuous barriers were eventually formed, closing the embayment again, producing the present enclosed-bay condition. The strong marine or open Gulf influence apparently extended up into the bay area as far as boring location XS 386 (Fig. 28). One Carbon-14 date indicates that this marine influence occurred about 6,000 years ago. There is also a strong indication that some of these borings may have been made in a rather narrow channel characterized by strong currents, since the deposits at about 45 feet in depth at stations XS 382 to 386 contain a great many remains of organisms adapted to and dependent on high current velocities. These remains are especially noticeable in the borings located in San Antonio Bay between the pre-Recent sand ridges, known as Live Oak Ridge (Price, 1933). This suggests that Live Oak Ridge has always been dissected by the Guadalupe River. As sea-level rose to the base of the ridge, inlet conditions would have prevailed until the channel was filled with clayey deposits. A new lagoon was then formed back of the newly formed barrier that is now Matagorda Island. With the formation of Matagorda Island (or perhaps first a series of small islands and spits creating open-bay or sound conditions) an enclosed-bay condition developed. The present barrier appears to have been formed between 2,000 and 4,000 years ago.

It is far more difficult to trace the history of depositional changes in the barrier island from the macrofauna alone, because the same fauna that lives in depths of 20–30 feet seaward of the barrier would also become incorporated in

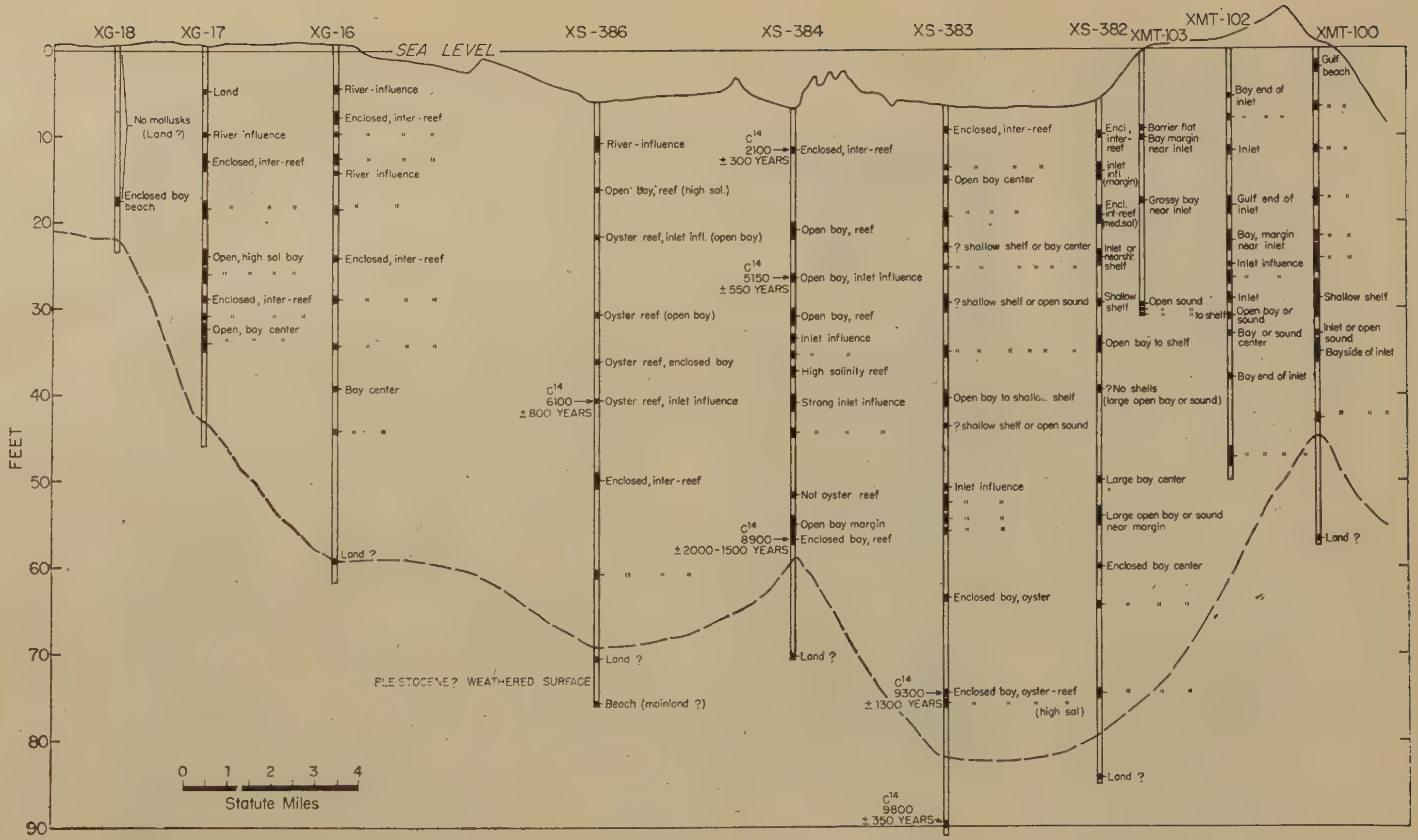

XG-18
XG-17
XG-16
XS-386
XS-384
XS-383
XS-382
XMT-103
XMT-102
XMT-100
SEA LEVEL
FEET
0
10
20
30
40
50
60
70
80
90
No mollusks (Land ?)
Enclosed bay beach
Land
River influence
Enclosed, inter-reef
Open, high sal bay
Enclosed, inter-reef
Open, bay center
Land ?
River-influence
Enclosed, inter-reef
River influence
Enclosed, inter-reef
Bay center
Land ?
River-influence
Open bay, reef (high sal.)
Oyster reef, inlet infl. (open bay)
Oyster reef (open bay)
Oyster reef, enclosed bay
Oyster reef, inlet influence
C14 6100 ± 800 YEARS
Enclosed, inter-reef
Land ?
Beach (mainland ?)
PLESTOCENE? WEATHERED SURFACE
C14 2100 ± 300 YEARS
Enclosed, inter-reef
Open bay, reef
C14 5150 ± 550 YEARS
Open bay, inlet influence
Open bay, reef
Inlet influence
High salinity reef
Strong inlet influence
Not oyster reef
Open bay margin
C14 8900 ± 2000-1500 YEARS
Enclosed bay, reef
Land ?
Enclosed, inter-reef
Open bay center
? shallow shelf or bay center
? shallow shelf or open sound
Open bay to shallo.. shelf
? shallow shelf or open sound
Inlet influence
Enclosed bay, oyster
C14 9300 ± 1300 YEARS
Enclosed bay, oyster-reef
(high sal)
C14 9800 ± 350 YEARS
Encl, inter-reef
inlet infl (margin)
Encl. int-reef med.sal)
Inlet or nearshr. shelf
Shallow shelf
Open bay to shelf
? No shells (large open bay or sound)
Large bay center
Large open bay or sound near margin
Enclosed bay center
Land ?
Barrier flat
Bay margin near inlet
Grassy bay near inlet
Open sound
to shelf
Bay end of inlet
Inlet
Gulf end of inlet
Bay, margin near inlet
Inlet influence
Inlet
Open bay or sound
Bay or sound center
Bay end of inlet
Gulf beach
Shallow shelf
Inlet or open sound
Bayside of inlet
Land ?
0
1
2
3
4
Statute Miles

FIG. 29.— Macrofaunal assemblage interpretations for each depth sampled (plus a few cuttings) in drillings taken from Guadalupe River Delta to Matagorda Island Gulf beach.

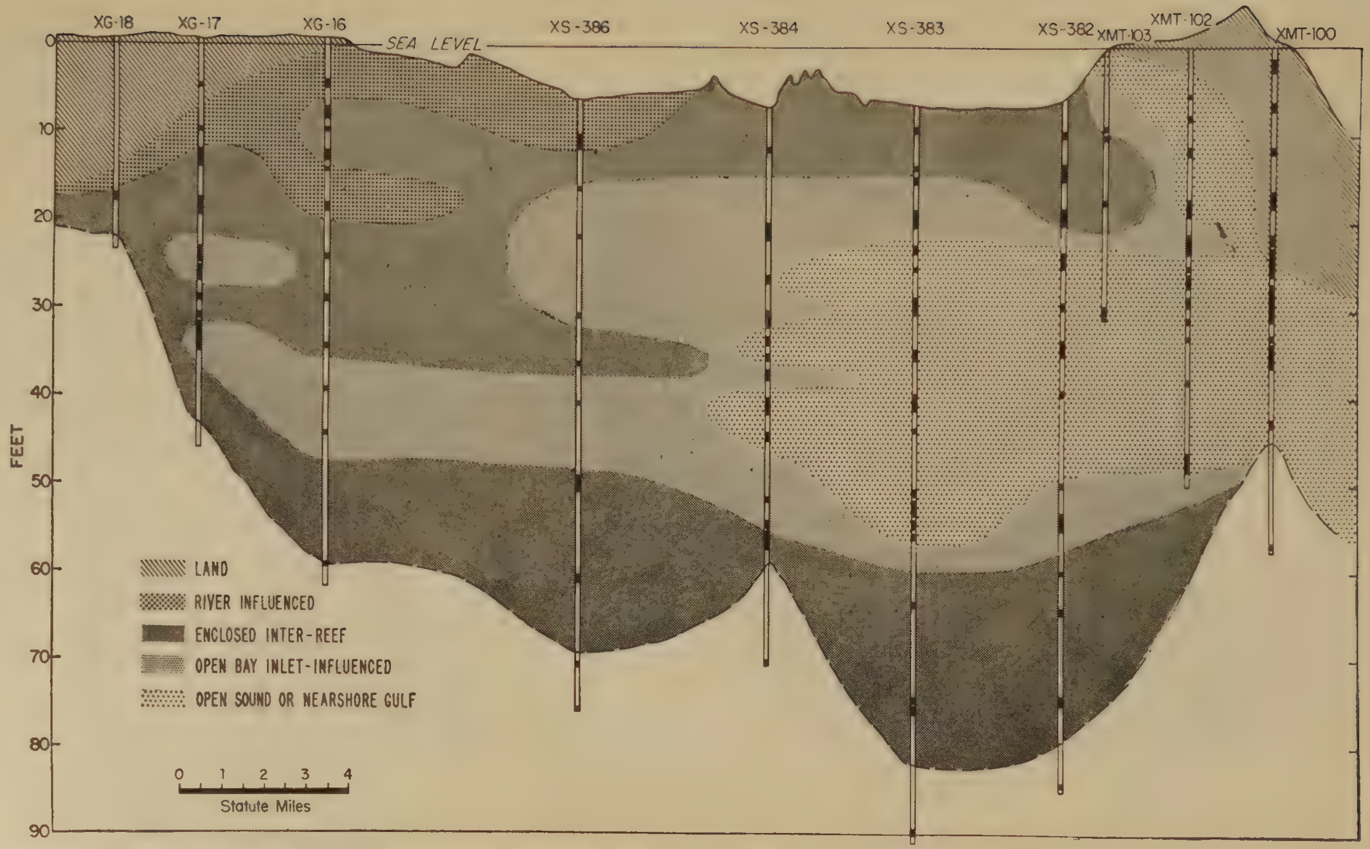


FIG. 30.—Generalized interpretation of cross section from Guadalupe River Delta to Gulf of Mexico, based on macrofaunal evidence.

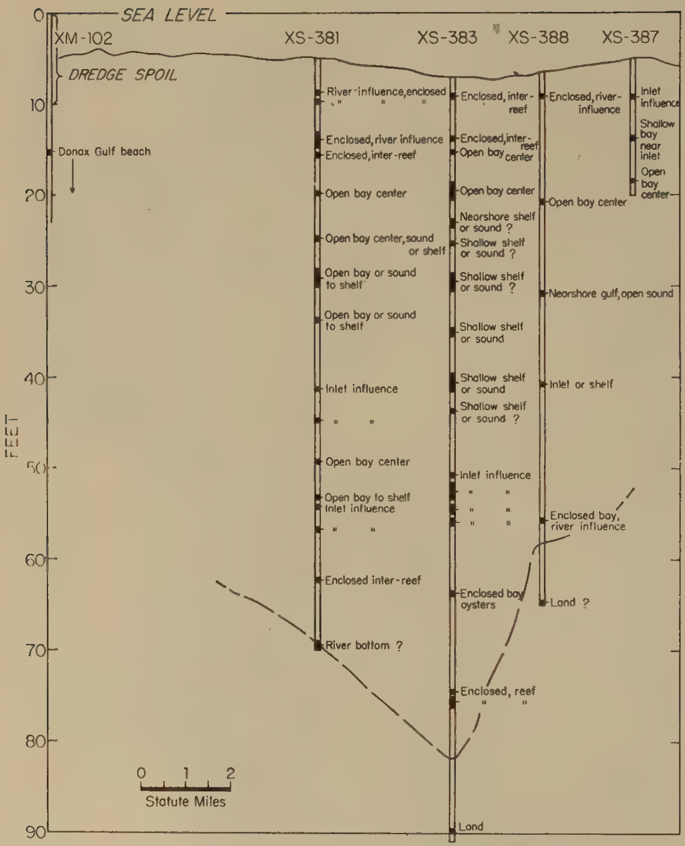

SEA LEVEL
XM-102
XS-381
XS-383
XS-388
XS-387
DREDGE SPOIL
Donax Gulf beach
River-influence, enclosed
" " "
Enclosed, river influence
Enclosed, inter-reef
Open bay center
Open bay center, sound or shelf
Open bay or sound to shelf
Open bay or sound to shelf
Inlet influence
" "
Open bay center
Open bay to shelf
Inlet influence
" "
Enclosed inter-reef
River bottom ?
Enclosed, inter-reef
Enclosed, inter-reef
Open bay center
Open bay center
Nearshore shelf or sound ?
Shallow shelf or sound ?
Shallow shelf or sound ?
Shallow shelf or sound
Shallow shelf or sound
Shallow shelf or sound ?
Inlet influence
" "
" "
" "
Enclosed bay oysters
Enclosed, reef
" "
Land
Enclosed, river-influence
Open bay center
Nearshore gulf, open sound
Inlet or shelf
Enclosed bay, river influence
Land ?
Inlet influence
Shallow bay near inlet
Open bay center
FEET
0
10
20
30
40
50
60
70
80
90
0 1 2
Statute Miles

FIG. 31a.—Macrofaunal assemblage interpretation for each depth sampled (plus a few cuttings) in drillings taken in Mesquite Bay and lower San Antonio Bay.

the beach deposits. In general, the presence and comparative abundance of the pelecypod, *Donax*, which lives entirely in or just outside the surf zone is a good indication of Gulf beach deposits. About 27 feet below the land surface, in the boring XMT 100, deposits containing relatively few *Donax* and an abundance of shells more indicative of a marine environment well outside the surf zone and depths of 20–50 feet were identified. This evidence suggests that the present barrier did not form at this location simultaneously with the arrival of sea-level to that location, and that a wide inlet or very open sound preceded the formation of the barrier island (Shepard and Moore, 1955, p. 1567).

Implications of this study to interpretations of Tertiary sediments.—Most of

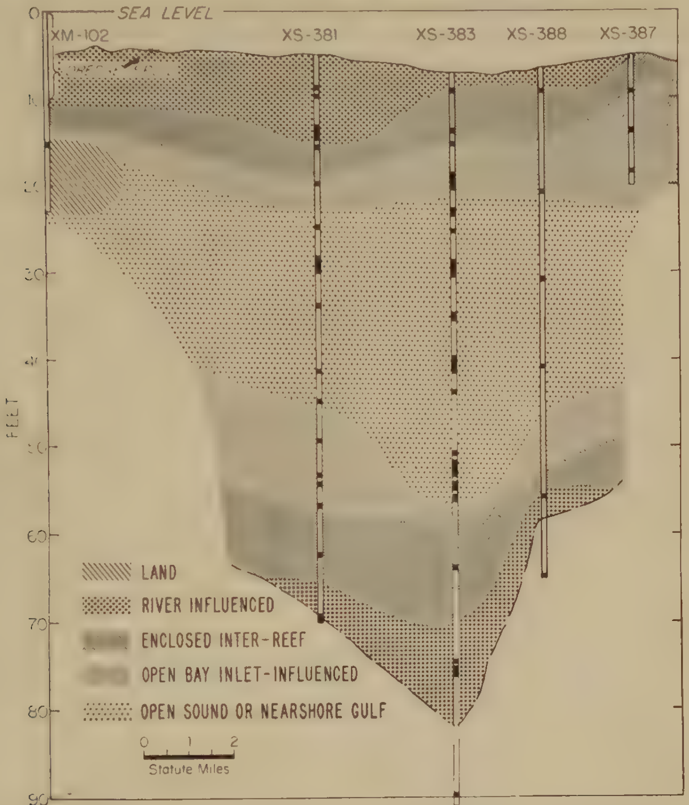

SEA LEVEL
XM-102
XS-381
XS-383
XS-388
XS-387
0
10
20
30
40
50
60
70
80
90
FEET
LAND
RIVER INFLUENCED
ENCLOSED INTER-REEF
OPEN BAY INLET-INFLUENCED
OPEN SOUND OR NEARSHORE GULF
0 1 2
Statute Miles

Fig. 31b.—Generalized interpretation of depositional history of Mesquite Bay and lower San Antonio Bay, based on macrofaunal evidence.

the important or characteristic species found in the sedimentary environments of the northern Gulf coast have also been found in the Pleistocene and Pliocene sediments of the Gulf and Atlantic coasts (Olsson and Harbison, 1953; Maury, 1920 and 1922; Parker, 1956, pp. 369–71). Some paleontologists and malacologists also consider many of the Miocene representatives of these species as the same as those living today, although this is a matter of personal opinion. What is more important, is that at least the Miocene and many of the Eocene and Paleocene forms are so similar in appearance to the Recent indicator forms, that only a well trained specialist can tell them apart. It was also observed from the literature that the same species were associated during the Tertiary as they are now. These observations suggest that evolution has been slow in many of the indicator mollusks; and the environments in which they lived during the Tertiary should have been similar. If the environments of the Tertiary were radically different, natural selection and environmental pressures would have brought about more morphologic changes and the same species or related species would not be found associated. There is always the possibility that the soft parts of these animals may have undergone considerable modification and adaptation that were not manifested in shell morphological changes. With these ideas in mind, some hope is offered in using the assemblages outlined in this paper to interpret Tertiary deposits.

SUMMARY

The following criteria for the recognition of depositional environments have been formulated from assessing the relationships between the distribution of benthic invertebrates and the present-day environments in which they live. These criteria should be useful in recognizing older bay and estuarine environments of deposition. These environments and invertebrates typical of them on the northern coast of the Gulf of Mexico are illustrated diagrammatically in Figure 32.

1. River-influenced, low-salinity bays are characterized by two basic forms of shelled organisms: massive-hinged, chalky pelecypods of the genus *Rangia*, and small, rather high-spired gastropods belonging primarily to the family Amnicolidae. Both appear to be inhabitants of clayey sediments brought down by rivers, and are generally distributed in open bays in agreement with the distribution of river water.

2. Enclosed bays of low to variable salinity are characterized by an increased number of species of invertebrates, and the occurrence of mollusk reefs (on the Gulf coast, *Crassostrea virginica*). These reefs act as natural barriers to the circulation, serving to separate this environment from the high-salinity and river-influenced parts of the bays. The reefs themselves constitute a specific assemblage of filter-feeding attached forms, while the "inter-reef" assemblage consists of rather small, thin-shelled pelecypods, adapted for deposit-feeding in the finer sediments which settle out between the reefs. The enclosed-bay deposits may also show periodic fluctuations of low- and high-salinity faunas in regions where there are long-period fluctuations of rainfall. On the Texas coast, the oyster reefs near inlets also respond to alternate droughts and floods with the alternation of species of oysters: *Ostrea equestris* during high salinities and *Crassostrea virginica* during low-salinity periods.

3. Open high-salinity bays have a distinctive fauna which can be subdivided into two assemblages: that of the bay margin and the assemblage of the bay center. Although salinity appears to be the controlling factor for the gross high-salinity bay fauna, substrate and circulation seem to be responsible for the separation of this fauna into two assemblages. The bay margins are predominantly sandy as a result of wave and current action; therefore, the characteristic filter-feeding faunas are those adapted for life in the relatively well sorted sandy sedi-

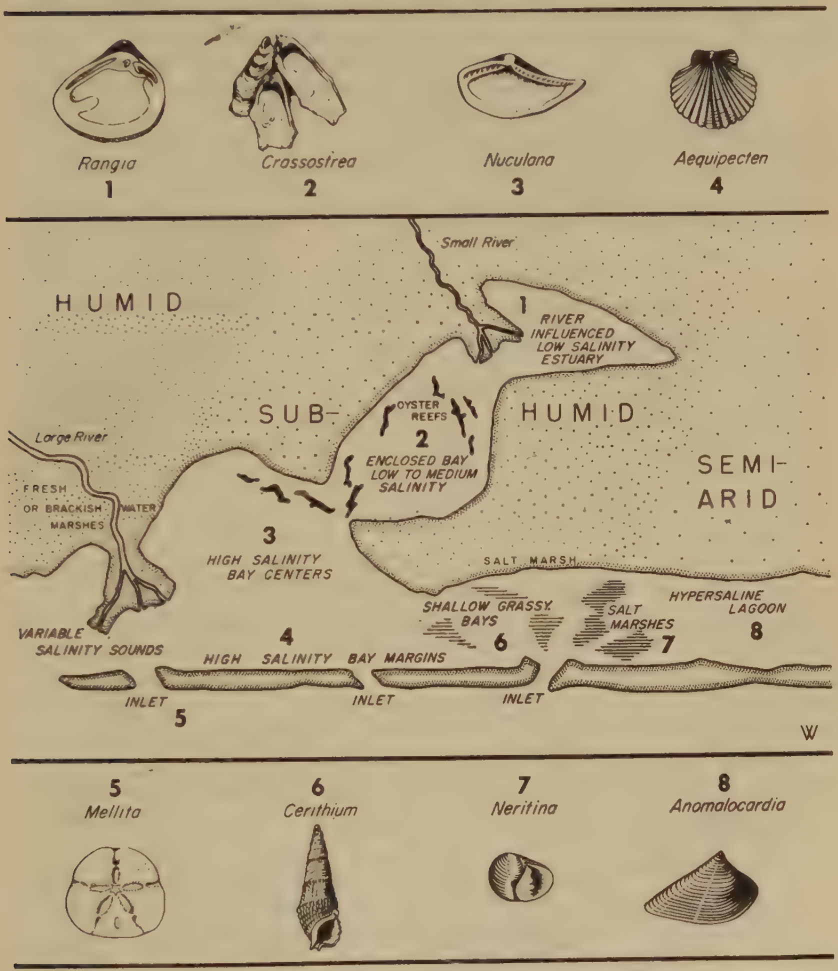

Rangia
1
Crassostrea
2
Nuculana
3
Aequipecten
4
Small River
HUMID
1
RIVER INFLUENCED LOW SALINITY ESTUARY
SUB-HUMID
OYSTER REEFS
2
ENCLOSED BAY LOW TO MEDIUM SALINITY
SEMI-ARID
Large River
FRESH OR BRACKISH WATER MARSHES
3
HIGH SALINITY BAY CENTERS
SALT MARSH
SHALLOW GRASSY BAYS
6
SALT MARSHES
7
HYPERSALINE LAGOON
8
VARIABLE SALINITY SOUNDS
4
HIGH SALINITY BAY MARGINS
INLET
5
INLET
INLET
W
5
Mellita
6
Cerithium
7
Neritina
8
Anomalocardia

FIG. 32.—Diagrammatic representation of bay and lagoonal macro-invertebrate environments in relation to general climatic provinces. Figured species is not everywhere found in the Texas region, but represents genus found in these environments throughout North America. *Rangia* (1) also found at Delta shores and distributaries of large rivers. *Nuculana* (3) also common in variable salinity sounds and pro-delta slopes. *Mellita* (5) migrates through inlets into bays. Certain species of *Neritina* (7) also found in fresh- or brackish-water marshes near large river mouths.

ments. On the Texas coast, the predominant organisms in this environment are scallops (*Aequipecten*), clams (*Mercenaria* and *Chione*), razor clams (*Tagelus*), and certain gastropods. On the other hand, the sediments of the bay centers are predominantly clayey, and the assemblage characteristic of high-salinity bay centers includes small pelecypods and gastropods capable of remaining at the surface of these soupy sediments. This assemblage is more dependent on the organic detritus contained in these sediments for food than the bay margin assemblage. It is also significant that the fine clayey sediments often completely lack a fauna producing hard parts (except for shell swept in from neighboring environments). This may be a partial explanation for the apparent lack of fossils in many marine shales.

4. Inlet areas on the Texas coast are characterized by the largest number of species of invertebrates, as the strong tidal currents typical of inlets bring in both shallow nearshore shelf faunas and bay faunas. As a result of stable, normal oceanic salinities and greater depths in the inlets, most marine invertebrates are more apt to survive there. It is also significant that many of the inlet indicator forms are adapted for attaching to the bottom or to objects on the bottom, a necessity in these areas of strong currents and hard sand bottom. Inlets should be recognized in older sediments on a faunal basis by the presence of large amounts of sand and shell material, echinoderm fragments, and a mixture of bay, Gulf, and indigenous species.

5. Hypersaline bays and lagoons are inhabited by many of the same species occurring in normal-salinity bays and lagoons, but the composition of the assemblages is quite distinct. Both in hypersaline and very low-salinity regions, the variability and adversity of the environment determine the species composition and comparative abundance of each species. In extremely variable hypersaline areas, the number of species is very low, and the number of living individuals is small also. In stable hypersaline areas (and stable, very low-salinity waters), the number of species is still small, but the number of living individuals is extremely large. As the salinity decreases or increases to normal values (along with relative stability), the number of species increases and the number of individuals per species decreases.

6. Several assemblages are recognized in hypersaline waters which are distinct enough to be useful in determining ancient environments of deposition. These are: (1) *shallow hypersaline bays or lagoons near inlets*, characterized by large numbers of gastropods and certain pelecypods which migrate between gulf and bay; (2) *open shallow hypersaline bay or lagoon*, characterized by abundant pelecypods, usually attached to the prevalent bottom vegetation; (3) *enclosed hypersaline lagoon*, identified by only a few species of closely related pelecypods, occurring in tremendous numbers; (4) *deep hypersaline bay with clayey substrate and variable salinity*, containing very few species of invertebrates and only scattered living individuals of each; and (5) *hypersaline bay with lower-salinity bay influence*, characterized by dominant hypersaline species, mixed with normal bay fauna.

7. It was demonstrated with a series of shallow borings that the depositional history of a small area can be deduced from the analysis of the macrofaunal remains, if they are present, although the study of the sediments and lithology should not be neglected.

8. Most of the invertebrate species used as indicators in this paper have existed since late Tertiary time, and closely related forms, identical in appearance, and living in the same association have existed throughout the Tertiary. This suggests similar environments of deposition have also existed throughout the Tertiary and that present-day faunal interpretations should be useful in solving the history of an area.

REFERENCES

ABBOTT, R. TUCKER, 1954, *American Seashells*. xiv, 541 pp., 40 pls. D. Van Nostrand Company, Inc., New York.

BAGGERMAN, B., 1953, "Spatfall and Transport of *Cardium edule* L.," *Archives Neerlandaises de Zoologie*, Tome 10, pp. 315–42.

BREUER, JOSEPH P., 1957, "An Ecological Survey of Baffin and Alazan Bays, Texas," *Pub. Inst. Marine Sci.*, Vol. 4, No. 2, pp. 134–55.

COLLIER, ALBERT, AND J. W. HEDGPETH, 1950, "An Introduction to the Hydrography of the Tidal Waters of Texas," *Pub. Inst. Marine Sci.*, Vol. 1, No. 2, pp. 120–94.

GALTSOFF, PAUL S., 1931, "Survey of Oyster Bottoms in Texas," *U. S. Bur. Fish. Inv. Rept.*, Vol. 6, pp. 1–30; 15 figs.

———, ET AL., 1954, "Gulf of Mexico, Its Origin, Waters and Marine Life," *Fishery Bull., U. S. Fish and Wildlife Serv.*, Vol. 55, 89. xiv, 604 pp.

GUNTER, GORDON, 1938, "Comments on the Shape, Growth and Quality of the American Oyster," *Science*, Vol. 88, No. 2293, pp. 546–47.

———, 1950, "Seasonal Population Changes and Distributions as Related to Salinity of Certain Invertebrates of the Texas Coast, Including Commercial Shrimp," *Pub. Inst. Marine Sci.*, Vol. 1, No. 2, pp. 7–51.

———, AND HENRY HILDEBRAND, 1951, "Destruction of Fishes and Other Organisms on South Texas Coast by the Cold Wave of January 28–February 3, 1951," *Ecology*, Vol. 32, No. 4, pp. 731–36.

HEDGPETH, JOEL W., 1947, "The Laguna Madre of Texas," *Trans. Twelfth North Amer. Wildl. Conf.*, pp. 364–80.

———, 1949, "The North American Species of *Macrobrachium* (River Shrimp)," *Texas Jour. Sci.*, Vol. 1, No. 3, pp. 28–38.

———, 1953, "An Introduction to the Zoogeography of the Northwestern Gulf of Mexico with Reference to the Invertebrate Fauna," *Pub. Inst. Marine Sci.*, Vol. 3, No. 1, pp. 110–224.

———, 1958, "Estuaries and Lagoons. II. Biological Aspects," *Geol. Soc. America Memoir 67*, Vol. 1, pp. 693–749.

HILDEBRAND, HENRY H., 1958, "Estudios Biologicos Preliminares Sobre la Laguna Madre de Tamaulipas," *Ciencia* (Mex.), Vol. 17, Nos. 7–9.

———, AND G. GUNTER, 1953, "Correlation of Rainfall with Texas Catch of White Shrimp, *Penaeus setiferus* (Linnaeus)," *Trans. Amer. Fish. Soc.*, Vol. 85, pp. 151–55.

KREGER, D., 1940, "On the Ecology of *Cardium edule* L.," *Archives Neerlandaises de Zoologie*, Tome 4, pp. 158–200.

LADD, HARRY S., 1951, "Brackish-Water and Marine Assemblages of the Texas Coast, with Special Reference to Mollusks," *Pub. Inst. Marine Sci.*, Vol. 2, No. 1, pp. 125–64.

———, JOEL W. HEDGPETH, AND RITA POST, 1957, "Environments and Facies of Existing Bays on the Central Texas Coast," *Geol. Soc. America, Memoir 67*, Vol. 2, pp. 599–640; 2 pls., 6 figs.

MAURY, C. J., 1920, "Recent Mollusca of the Gulf of Mexico and Pleistocene and Pliocene Species from the Gulf States. Part I: Pelecypods," *Bull. Amer. Paleon.*, Vol. 8, pp. 1–116; 1 pl.

———, 1922, "Recent Mollusca of the Gulf of Mexico and Pleistocene and Pliocene Species from the Gulf States. Part II: Scaphopoda, Gastropoda, Amphineura, Cephalopoda," *ibid.*, Vol. 9, pp. 32–172.

MCCLURE, C. D., H. F. NELSON, AND W. B. HUCKABAY, 1958, "Marine Sonoprobe System, New Tool for Geologic Mapping," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 42, No. 4, pp. 701–16; 9 figs.

MITCHELL, J. D., 1894, "List of Texas Mollusca," *Victoria, Texas: Times Steam Print*, Vol. 22.

NORRIS, ROBERT M., 1953, "Buried Oyster Reefs in Some Texas Bays," *Jour. Paleon.*, Vol. 27, pp. 569–76; 5 figs.

Olsson, Axel A., and Anne Harbisan, 1953, "Pliocene Mollusca of Southern Florida, with Special Reference to Those from North Saint Petersburg," *Acad. Nat. Sci. Philadelphia Mon. 8.* 457 pp., 65 pls.

Parker, Frances L., F. B Phleger, and J. F. Peirson, 1953, "Ecology of Foraminifera from San Antonio Bay and Environs, Southwest Texas," *Cushman Found. Foram. Res. Spec. Pub. 2.* 75 pp.

Parker, Robert H., 1955, "Changes in Invertebrate Fauna, Apparently Attributable to Salinity Changes, in the Bays of Central Texas," *Jour. Paleon.*, Vol. 29, No. 2, pp. 193–211; 8 figs.

———, 1956, "Macro-Invertebrate Assemblages as Indicators of Sedimentary Environments in East Mississippi Delta Region," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 40, No. 2, pp. 295–376; 32 figs., 8 pls.

Phleger, Fred B, 1956, "Significance of Living Foraminiferal Populations Along the Central Texas Coast," *Contrib. Cushman Found. Foram. Res.*, Vol. 7, Pt. 4, pp. 106–51; 20 figs.

———, and Robert R. Lankford, 1957, "Seasonal Occurrences of Living Benthonic Foraminifera in Some Texas Bays," *ibid.*, Vol. 8, Pt. 3, pp. 93–105; 6 figs.

Price, W. Armstrong, 1933, "Role of Diastrophism in Topography of Corpus Christi Area, South Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 8, pp. 907–62; 17 figs.

———, 1947, "Equilibrium of Form and Forces in Tidal Basins of Coast of Texas and Louisiana," *ibid.*, Vol. 31, No. 9, pp. 1619–63.

Pritchard, D., 1952, "Salinity Distribution and Circulation in the Chesapeake Bay Estuarine System," *Jour. Mar. Res.*, Vol. 11, No. 2, pp. 106–23; 11 figs.

Puffer, E. L., 1953, "Potential Megafossils of the Rockport, Texas Area and Their Distribution," *unpubl. M. A. dissertation, Univ. California*, Berkeley. 144 pp., 14 maps and charts.

———, and William K. Emerson, 1953, "The Molluscan Community of the Oyster Reef Biotope on the Central Texas Coast," *Jour. Paleon.*, Vol. 27, pp. 536–44; 1 pl.

Pulley, Thomas E., 1952, "An Illustrated Check List of the Marine Mollusks of Texas," *Texas Jour. Sci.*, Vol. 4, pp. 167–99; 13 pls.

———, 1953, "A Zoogeographic Study Based on the Bivalves of the Gulf of Mexico," *unpub. Ph.D. dissertation, Harvard Univ.* (abst. in *Ann. Rept. Malacological Union*, 1952, pp. 2–3).

Rusnak, Gene A. (in press), "Sediments of the Laguna Madre."

Shepard, Francis P., 1953, "Sedimentation Rates in Texas Estuaries and Lagoons," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 37, No. 8, pp. 1919–34.

———, "Nomenclature Based on Sand-Silt-Clay Ratios," *Jour. Sed. Petrology*, Vol. 24, No. 3, pp. 151–58.

———, 1956, "Late Pleistocene and Recent History of the Central Texas Coast," *Jour. Geol.*, Vol. 64, No. 1, pp. 56–69.

———, and David G. Moore, 1955, "Central Texas Coast Sedimentation: Characteristics of Sedimentary Environment, Recent History and Diagenesis," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 39, No. 8, pp. 1463–1593; 75 figs.

———, and Gene A. Rusnak, 1957, "Texas Bay Sediments," *Pub. Inst. Mar. Sci.*, Vol. 4, No. 2, pp. 5–13.

Simmons, Ernest G., 1957, "An Ecological Survey of the Upper Laguna Madre of Texas," *Pub. Inst. Marine Sci.*, Vol. 4, No. 2, pp. 156–200; 13 figs.

Swain, F. M., 1955, "Ostracoda of San Antonio Bay, Texas," *Jour. Paleon.*, Vol. 29, No. 4, pp. 561–646.

Taylor, Walter P., 1934, "Significance of Extreme or Intermittent Conditions in Distribution of Species and Management of Natural Resources, with a Restatement of Liebig's Law of Minimum," *Ecology*, Vol. 15, No. 4, pp. 374–79.

Thorson, Gunnar, 1958, "Bottom Communities (Sublittoral or Shallow Shelf)," *Geol. Soc. America Memoir 67*, Vol. 1, pp. 461–534; 20 figs.

Verwey, J., 1952, "On the Ecology of Distribution of Cockle and Mussel in the Dutch Waddensea, Their Role in Sedimentation and the Source of Their Food Supply," *Archives Neerlandaises de Zoologie*, Tome 10, pp. 171–239; 6 figs.

Williams, W. T., and U. G. Whitehouse, 1952, "Analysis and Interpretation of Physical Oceanographic Data from the Rockport Area," *Amer. Petrol. Inst. Project 51*, 4th Quar. Rept., Appen. IV, Mimeo. report, pp. 28–38.

APPENDIX

TABLE II. CHECK LIST OF INVERTEBRATES, BY ENVIRONMENTS, IN THE ROCKPORT, TEXAS REGION AND LAGUNA MADRE

Species Rockport Region	River Infl.	Enclos. Bays	Low Sal. Reef	High Sal. Reef	Open Bay Center	Open Bay Margin	Inlet Infl.	Shallow Hypersal.
Littoridina sphinctostoma Abbott & Ladd, 1951 G	xxxxx	----						
Macoma mitchelli Dall, 1895 P	xxxxx	xxxxx			----	--		
Rangia cuneata (Gray, 1831) P	xxxxx	--x--				-		
Mulinia lateralis (Say, 1822) P	--x--	xxxxx			xxxxx	xxxxx	-----	-----
Tagelus plebeius (Solander, 1786) P	-xxx-				--	--		
Amphiodia limbata (Grube) E		xxxxx			xxxxx	xxx		
Anachis obesa (C. B. Adams, 1845) G		xxxxx		xxxxx	-----	-xxx-	xxxxx	--
Crassostrea virginica (Gmelin, 1791) P	-----	xxxxx	xxxxx	-xxx-	-----	-----	-----	---
Brachidontes recurvus (Rafinesque, 1820) P			xxxxx	--x--		--	--	
Bittium varium (Pfeiffer, 1840) G			-x-	xxxxx	-	--	-xx--	xxxxx
Crepidula plana Say, 1822 G		--	-x-	xxxxx	-xx--	xxxxx	xxxxx	-----
Mitrella lunata (Say, 1826) G			-xx-	xxxxx			xxxxx	-----
Anachis avara semiplicata (Stearns, 1873) G		--		xxxxx	----	xxxxx	. -xxx-	--
Anomia simplex d'Orbigny, 1842 P		---		xxxxx	-xx--	xxxxx	xxxxx	--
Astrangia astreiformis Milne-Edwards and Haime, 1849 Co				xxxxx		--	xxxxx	
Brachidontes exustus (Linné, 1758) P		---		xxxxx	xxxxx	xxxxx	xxxxx	xx
Bugula neritina (Linné, 1758) Br				xxxxx	xxxxx	xxxxx	xxxxx	xx
Crangon heterochelis (Say) Cr				xxxxx			xxxxx	
Diplothyra smithi (Tryon, 1862) P				xxxxx				
Ischnochiton papillosus (C. B. Adams, 1845) Chiton				xxxxx			xxxxx	
Menippe mercenaria (Say) Cr				xxx				
Neopenope texana sayi (Stimpson) Cr				xxxxx			xxx	
Odostomia impressa (Say, 1821) G		xx-		xxxxx		-xxx-	---	-----
Ostrea equestris Say, 1834 P				xxxxx			xxxxx	--x--
Petrolisthes armatus (Gibbes) Cr				xxxxx				
Seila adamsi (H. C. Lea, 1846) G				--x--			-----	
Thais haemastoma floridana (Conrad, 1837) G				xxxxx		-	xxxxx	x
Thais haemastoma haysae Clench, 1927 G			---	-x-			-x-	
Triphora perversa nigrocinta (C. B. Adams, 1839) G				----				
Anadara transversa (Say, 1822) P		---		xxxxx	xxx	--x--	xxxxx	--
Abra aequalis (Say, 1822) P	-	-----			--x--		xxxxx	------
Chione cancellata (Linné, 1767) P		---			xxxxx	-xxx-	xxxxx	-----
Diplodonta punctata (Say, 1822) P					-xx--	-x-		
Diplodonta semiaspera Philippi, 1836 P					-x-	-	-xx-	-
Ensis minor Dall, 1899 P		-xx--			xxxxx	xxxxx	---	
Loliguncula brevis (de Blainville, 1823) Ceph.					xxxxx		xxxxx	
Nassarius acutus (Say, 1822) G		---			-xxx-	---	-xx--	
Nuculana acuta (Conrad, 1834) P	--	-----			xxxxx	-xxxx	xxxxx	--
Nuculana concentrica (Say, 1824) P	-	-x-			xxxxx	---	---	
Pandora trilineata (Say, 1822) P					xxxxx	xxxxx	-xxx-	
Periploma fragile (Totten, 1835) P					-xxx-			
Retusa canaliculata (Say, 1827) G		-----			-xxx-	---	-----	------
Semele proficua (Pulteney, 1799) P		--			--x--		-xx--	-

Table II (cont.) - 2 -

Species	River Infl.	Enclos. Bays	Low Sal. Reef	High Sal. Reef	Open Bay Center	Open Bay Margin	Inlet Infl.	Shallow Hypersal.
Truncatella pulchella Pfeiffer, 1839 G					--			
Trachycardium muricatum (Linné, 1758) P					-xx--	xx-xx	xxxxx	
Anadara campechiensis (Gmelin, 1790) P		---			--x--	xxx	xxxxx	--
Tagelus divisus (Spengler, 1794) P					-----	xxxxx	-xx-	
Aequipecten irradians amplicostatus (Dall, 1898) P					---	xxxxx	xxxxx	x-
Astarte nana E. A. Smith, 1881 P						--x--	---	
Cerithiopsis greenei (C. B. Adams, 1839) G						--		
Cerithium variabile (C. B. Adams, 1848) G						--x--		xxxxx
Cyclinella tenuis (Récluz, 1852) P						-xxx-	-xxx-	
Cyrtopleura costata (Linné, 1758) P					--	----	----	
Dinocardium robustum (Solander, 1786) P						---	---	
Ervillia concentrica (Gould, 1862) P		---				xxxxx		
Laevicardium mortoni (Conrad, 1830) P		-				xxxxx	--x-	xxxxx
Littorina ziczac (Gmelin, 1790) G						-xxx-	xxxxx	
Lucina crenella (Dall, 1901) P		--			--	-----	-----	--
Lyonsia floridana hyalina (Conrad, 1846) P						xxxxx	-xx-	
Macoma constricta (Bruguiere, 1792) P					-----	-xx	-	----
Macoma brevifrons (Say, 1834) P						xxxxx	--	
Macoma limula Dall, 1895 P						x		
Mactra fragilis Gmelin, 1790 P						--x--		
Melampus bidentatus Say, 1822 G						-xx-		xxxxx
Mecenaria m. campechiensis (Dall, 1902) P					--	--xx-	xxxxx	
Mysella planulata (Stimpson, 1857) P		-----			-----	--x--	-xxx-	
Nassarius vibex (Say, 1822) G					-----	xxxxx	---	-xxx-
Neritina virginea (Linné, 1758) G						----		-----
Odostomia bisurturalis (Say, 1821) G						--		
Palaemonetes, sp. Cr.						xxxxx	xxxxx	
Periploma inequale (C. B. Adams, 1842) P						-xx--	-----	
Petricola pholadiformis Lamarck, 1818 P						---	---	
Polinices duplicatus (Say, 1822) G					-----	-xxx-	xxxxx	
Phacoides pectinatus (Gmelin, 1790) P						-----		--x--
Pseudocyrena floridana (Conrad, 1846) P						--x--		-----
Tellina alternata Say, 1822 P						x-	-x-	
Thyone mexicana Deichmann, 1946 E						xx		
Turbonilla incisa Bush, 1899 G					---	-----	-xxx-	
Vermicularia fargoi Olsson, 1951 G						-----	-----	-----
Bulla occidentalis A. A. Adams, 1850 G						--	--	-----
Cerithidea pliculosa (Menke, 1829) G						-----	-----	--x--
Macoma tenta (Say, 1834) P						x-	xx-xx	
Anadara brasiliana (Lamarck, 1819) P						--	-----	
Anachis avara similis (Ravenel, 1861) G							xx	
Arbacia punctulata (Lamarck, 1816) E							xxx	

Table II (cont.) —3—

Species	River Infl.	Enclosed Bays	Low Sal. Reef	High Sal. Reef	Open Bay Center	Open Bay Margin	Inlet Infl.	Shallow Hypersal.
Atrina seminuda (Lamarck, 18[illegible]) P							-xx--	
Busycon contrarium (Conrad, 1840) G							xxxxx	
Busycon spiratum (Lamarck, 1816) G							--	
Cantharus cancellarius (Conrad, 1846) G							xxxxx	—xx-
Cantharus tinctus (Conrad, 1846) G							xxxxx	
Cardita floridana (Conrad, 1838) P							-----	----
Chaetopleura apiculata Say, 1839 Chiton							x	
Chione clenchi Pulley, 1952 P							-x	
Corbula contracta Say, 1822 P						---	xxxxx	
Corbula swiftiana C. B. Adams, 1852 P							----	
Crassinella lunulata (Conrad, 1834) P					---	-x-	xxxxx	
Crepidula fornicata (Linné, 1758) G							-xxx-	-----
Crepidula glauca convexa Say, 1822 G						--x--	-xx--	xxxxx
Cyclichna bidentata (d'Orbigny, 1841) G							—	
Cyclostremiscus trilix (Bush, 1885) G							--	
Dentalium texasianum Philippi, 1849 Scaph.		—			-----	---	-xxxx	
Diodora cayenensis (Lamarck, 1822) G						--	-xxx-	-
Donax variabilis texana Philippi, 1847 P						—	---	
Dosinia discus (Reeve, 1850) P					-----	-----	--x--	
Eontia ponderosa (Say, 1822) P							-xxx-	
Epitonium angulatum (Say, 1831) G							-x	-
Epitonium rupicolum (Kurtz, 1860) G							-x-	
Epitonium tollini Bartsch, 1938 G							—	
Hemipholas elongata (Say, 1825) E							xxxxx	
Heterocrypta granulata (Gibbes, 1849) Cr							xxxxx	
Kurtziella perryae Bartsch and Rehder, 1939 G							x-	
Labiosa plicatella (Lamarck, 1818) P							—	
Leptogorgia setacea (Pallas, 1766) Co							xxxxx	
Libinia emarginata Leach Cr				xx			xxxxx	
Littorina irrorata (Say, 1822) G						----	xxxxx	xxxxx
Lucina amiantus (Dall, 1901) P							-xxx-	
Luidia alternata (Say, 1825) E							x	
Luidia clathrata (Say, 1825) E							xx-xx	
Lytechinus variegatus (Lamarck, 1816) E							x	
Mellita quinquiesperforata (Leske) E							xxxxx	
Modulus modulus (Linné, 1758) G						----	--x--	--x--
Natica pusilla Say, 1822 G							-xxx-	-
Neosimnia uniplicata (Sowerby, 1848) G							xx	
Oliva sayana Ravenel, 1834 G							--	-
Olivella mutica (Say, 1822) G							--	
Ophiolepis elegans Lütken, 1859 E							xxxxx	
Ophiothrix angulata (Say, 1825) E							x	
Ovalipes guadalupensis (Saussure) Cr							xxxx	

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Table II (Cont.) - 4 -

Species	River Infl.	Enclosed Bays	Low Sal. Reef	High Sal. Reef	Open Bay Center	Open Bay Margin	Inlet Infl.	Shallow Hypersal.
Pteria colymbus (Bolten Röding, 1798) P							-	-
Pyramidella crenulata Holmes, 1859 G							—	—
Quadrans lintea Conrad, 1837 P							--	
Renilla mülleri Kölliker Co							xxxxx	
Sinum perspectivum (Say, 1831) G							xxx	
Tellidora cristata (Récluz, 1842) P							-xxxx	
Tellina tayloriana Sowerby, 1867 P							—x--	
Tellina versicolor De Kay, 1834 P							—x—	
Terebra dislocata (Say, 1822) G							x	
Turbonilla hemphilli Bush, 1899 G							----	-
Turbonilla interrupta Totten, 1835 G							--x--	
Vitrinella, sp. G							-x	
Amygdalum papyria (Conrad, 1846) P								-xx-
Anodontia alba Link, 1807 P						---	---	xxxxx
Anomalocardia cuneimeris (Conrad, 1846) P					-	--x--	-----	xxxxx
Brachidontes citrinus (Röding, 1798) P								xx
Caecum nitidum Stimpson, 1851 G								-----
Caecum pulchellum Stimpson, 1851 G								----
Fasciolaria hunteria (Perry, 1811) G								---
Haminoea elegans (Gray, 1825) G						--	-	----
Laevicardium laevigatum (Linné, 1758) P						--		--
Melanella conoidea (Kurtz and Stimpson, 1854) G								--
Niso interrupta Sowerby, 1834 G								---
Prunum apicinum (Menke, 1828) G								--
Rissoina chesneli (Michaud, 1832) G								--
Semele purpurescens (Gmelin, 1790) P							-	--
Tegula fasciata (Born, 1780) G								----

Laguna Madre Region	Inlet-Hypersal.	Open Hypersal.	Enclos. Hypersal.	Deep Hypersal.	Low Sal. Bay Infl.	Hypersal.
Aequipecten irradians amplicostatus (Dall, 1898) P	xxxxx				-	
Anachis avara semiplicata (Stearns,1873) G	xxxxx	—	-		-	
Anachis obesa (C. B. Adams, 1845) G	-x					
Anadara brasiliana (Lamarck, 1819) P	—					
Anadara transversa (Say, 1822) P	—x—	-			—	
Anomia simplex d'Orbigny, 1842 P	--x—		--		---	
Atrina seminuda (Lamarck, 1819) P	—					
Cantharus cancellarius (Conrad, 1846) G	-xx-					
Cantharus tinctus (Conrad, 1846) G	xxxxx					
Chione cancellata (Linné, 1767) P	xxxxx	—	--		—	
Crangon heterochelis (Say) Cr	xx					
Crepidula glauca convexa Say, 1822 G	xxxxx	-x	—		—	

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Table II (Cont.) - 5 -

Species	Inlet Hypersal.	Open Hypersal.	Enclos. Hypersal.	Deep Hypersal.	Low Sal. Bay Infl	Hypersal.
Crepidula fornicata (Linné, 1758) G	-					
Crepidula plana Say, 1822 G	—x—				-	
Cyclinella tenuis (Réclus, 1852) P	-					
Cyrtopleura costata (Linné, 1758) P	xx					
Diplodonta semiaspera Philippi, 1847 P	—				-	
Epitonium multistriatum (Say, 1826) G	—		-			
Iscnochiton papillosus (C. B. Adams, 1845) Chit.	-x					
Littorina angulifera (Lamarck, 1822) G	xxx					
Littorina nebulosa (Lamarck, 1822) G	xxx					
Littorina zicsac (Gmelin, 1790) G	xxxxx					
Lytechinus variegatus (Lamarck, 1816) E	x					
Macoma tenta (Say, 1834) P	———					
Mellita quinquiesperforata (Leske) E	—					
Natica pusilla Say, 1822 G	-					
Neopenope texana sayi (Stimpson) Cr	xxxxx					
Neritina virginea (Linné, 1758) G	-xxx-		——--			
Nuculana acuta (Conrad, 1834) P	-xx--				-	
Odostomia impressa (Say, 1821) G	—					
Ophiothrix angulata (Say, 1825) E	xx					
Ostrea equestris Say, 1834 P	—x—	-			—	
Polinices duplicatus (Say, 1822) G	-x-		-			
Portunus gibbesi (Stimpson, 1859) Cr.	x					
Pyramidella crenulata Holmes, 1859 G	-					
Pyramidella fusca (C. B. Adams, 1839) G	—				-	
Hiatella arctica (Linné, 1767) P ?	-					
Tegula fasciata (Born, 1780) G	--——					
Tellidora cristata (Réclus, 1842) P	-					
Tellina versicolor De Kay, 1843 P	-x					
Thais haemastoma floridana (Conrad, 1837) G	xxx					
Trachycardium muricatum (Linné, 1758) P	——					
Turbonilla interrupta Totten, 1835 G	-x-	-	--		-	
Vermicularia fargoi Olsson, 1951 G	-x					
Vitrinella, sp. G	-					
Abra aequalis (Say, 1822) P	--x—	-	-		——	
Brachidontes citrinus (Röding, 1798) P	-xx-	-xx—	--x--	—	———	
Brachidontes exustus (Linné, 1758) P	—	-	-			
Brachidontes recurvus (Rafinesque, 1820) P	—	-			-	
Bulla occidentalis A. A. Adams, 1850 G	———		-		———	
Cerithidea pliculosa (Menke, 1829) G	——-	——	——		——	
Cerithium variabile (C. B. Adams, 1848) G	--x—	—	--x—		-----	
Corbula contracta Say, 1822 P	-				-	
Donax tumida Philippi, 1848 P	-	-	-		-	

Table II (Cont.) - 6 -

Species	Inlet Hypersal.	Open Hypersal.	Enclos. Hypersal.	Deep Hypersal.	Low Sal. Bay Infl. Hypersal.
Kurtziella perryae Bartsch and Rehder, 1939 G	-		-		
Macoma constricta (Bruguiere, 1792) P	---	-	--		
Modulus modulus (Linné, 1758) G	--	-	--		
Nassarius vibex (Say, 1822) G	-xxx-	xx	-----		-x-
Retusa canaliculata (Say, 1827) G	----	--	---		--
Amygdalum papyria (Conrad, 1846) P		xxxxx	-		-
Bittium varium (Pfeiffer, 1840) G	x	xxxxx	----		----
Haminoea elegans (Gray, 1825) G		--			
Laevicardium mortoni (Conrad, 1830) P	--x--	xxxxx	----		-xx
Macoma brevifrons (Say, 1834) P	-xx--	xxxxx	----		----
Mactra fragilis Gmelin, 1790 P	---	--x--	--		x
Mitrella lunata (Say, 1826) G	-	-x-			
Pseudocyrena floridana (Conrad, 1846) P		xxxxx	-----		--
Tagelus divisus (Spengler, 1794) P	--	-----			--
Truncatella pulchella Pfeiffer, 1839 G		-			
Anomalocardia cuneimeris (Conrad, 1846) P	-----	xxxxx	xxxxx	-----	xxxxx
Mulinia lateralis (Say, 1822) P	-xx--	xxxxx	xxxxx	--xx-	xxxxx
Tellina tampaensis Conrad, 1866 P	--	-xxxx	xxxxx		--x--
Caecum nitidum Stimpson, 1851 G			--	-	
Cardita floridana (Conrad, 1838) P	-	-	--		
Lucina crenella (Dall, 1901) P	-		---	-	-
Melampus bidentatus Say, 1822 G			--		-
Odostomia bisuturalis (Say, 1821) G		--	-xx-		-x
Olivella mutica (Say, 1822) G			--		
Acteon punctostriatus (C. B. Adams, 1840) G	-	---	--	-xx	--
Astarte nana E. A. Smith, 1881 P					-
Callinectes sapidus Rathbun Cr		x	-		xxxxx
Crassinella lunulata (Conrad, 1834) P					-
Crassostrea virginica (Gmelin, 1791) P	----		---		--x--
Dentalium texasianum Philippi, 1849 Scaph.					-
Ensis minor Dall, 1899 P					-x-
Lucina amiantus (Dall, 1901) P					--
Lyonsia floridana hyalina (Conrad, 1846) P	-				x
Phacoides pectinatus (Gmelin, 1790) P	-x	--	----	-	-xx--
Tagelus plebeius (Solander, 1786) P		--			--

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x = Living   Frequency of x's and -'s indicate relative abundance.
- = Dead Shell

P - Pelecypods
G - Gastropods
E - Echinoderms
Cr - Crustaceans
Co - Coelenterates
Br - Bryozoa
Ceph - Cephalopods
Scaph - Scaphopods

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The Measurement of Thermal Conductivity of Deep-Sea Sediments by a Needle-Probe Method[1]

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Abstract—The transient heating of a needle probe is used to measure the thermal conductivity of deep-sea sediments in 10 minutes or less. An accuracy of 3 to 4 per cent compares favorably with steady-state methods, and measurements by both methods on the same sediments show good agreement. Thermal diffusivity of deep-sea sediments is shown to be proportional to thermal conductivity, in agreement with theoretical expectations.

INTRODUCTION

Until recently, apparatus for the measurement of thermal conductivity of solid materials of lower conductivity than metals, such as soils and clays, has generally been of one type; namely, the steady-state hot-plate method. This consists of a small cylindrical prism of the sample, the ends of which are bound by metal slabs of higher conductivity. Heat is supplied at a known rate to one of the slabs and taken away at the other, so that the specimen is a part of the path of uniform flow of heat. Under these conditions, the temperature difference on both sides of the specimen is measured, and the conductivity can readily be calculated. Several hours may be required for the determination of the conductivity of a specimen with this method because of the long time necessary for the attainment of equilibrium and the need for several samples to be measured. Recent improvements [*Beck*, 1957] have reduced this time somewhat.

Measurements of heat flow through the floor of the ocean require an accurate determination of the thermal conductivity of the sediment where the thermal-gradient measurement is made. The sediment is brought to the ocean surface in a coring tube, where there is a need for rapid determination of the conductivity at many points without serious disturbance of the core sample. These requirements have led to the development of a transient technique for measuring thermal conductivity.

DESCRIPTION AND THEORY

Thermal conductivity—Basically, the transient technique closely approximates an infinitely long, continuous line source of heat in an infinite medium, the temperature near the line source being measured as a function of time. The method was first used to measure the thermal conductivity of liquids [*Van der Held and others*, 1953], although convection posed difficulties not encountered with soil and deep-sea-sediment measurements. Similar techniques have been developed for measuring the thermal conductivity of insulating materials by *D'Eustachio and Schreiner* [1952], who used thermocouples as temperature-sensing elements. Likewise, equipment for this measurement has been successfully applied to the determination of thermal conductivity of soils [for example, *Mason and Kurtz*, 1952; *Beuttner*, 1955; *Lachenbruch*, 1957].

The measurement of thermal conductivity of a deep-sea sediment contained in a tube 2 inches in diameter requires similar, but some-

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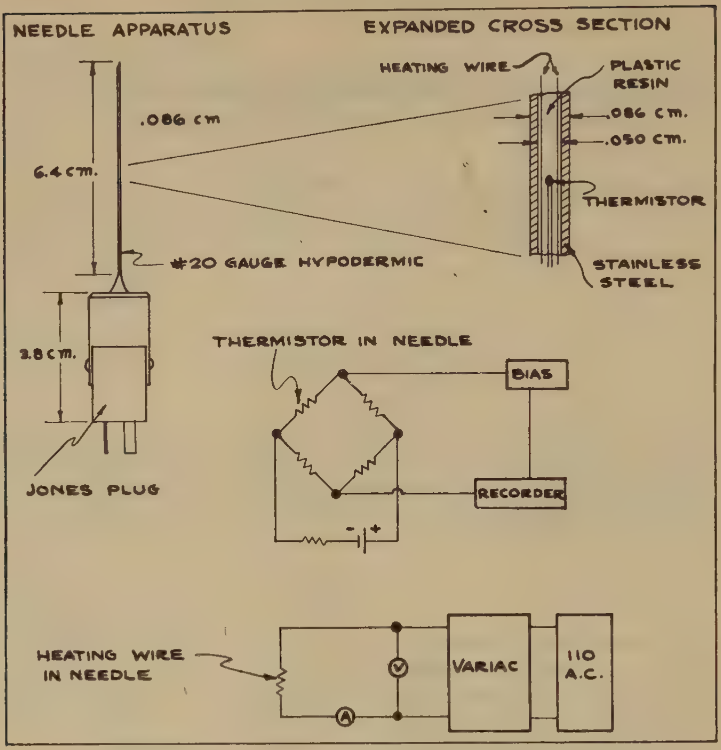
NEEDLE APPARATUS
EXPANDED CROSS SECTION
HEATING WIRE
PLASTIC RESIN
.086 cm
.086 cm.
.050 cm.
6.4 cm.
THERMISTOR
#20 GAUGE HYPODERMIC
STAINLESS STEEL
3.8 cm.
THERMISTOR IN NEEDLE
BIAS
JONES PLUG
RECORDER
HEATING WIRE IN NEEDLE
V
A
VARIAC
110 A.C.

Fig. 1—Needle-probe apparatus for measuring conductivity.

what smaller apparatus than is used for soils. Figure 1 shows the first instrument developed for this use by *Maxwell* [1958] and described by *Bullard and others* [1956]. Briefly, the probe of Figure 1 is a hypodermic needle enclosing a single loop of heating wire and a temperature sensing thermistor placed at the middle of the needle.

The theory for the apparatus has been worked out in considerable detail by *Jaeger* [1956, 1958], among others. Their analyses have shown that the rise of temperature of the probe is given to a good approximation by

$$T = \frac{q}{4K\pi}(\ln 4\alpha t/Ba^2)$$

where

t = time
q = heat input per unit length per unit time
K = thermal conductivity of sediment sample
α = thermal diffusivity of sediment sample
a = probe radius
B = constant = 1.7811

This relationship is valid when t is large compared with a^2/α. A plot of T versus $\ln t$ will then give a straight line, the slope of which determines K, for known values of q. Depending on the sediment, a^2/α for this needle probe ranges between ½ and 1 second. It is experimentally observed that the linear asymptote on a plot of T versus $\ln t$ is closely approached after 10 seconds. This is consistent with the theoretical analysis [*Jaeger*, 1958] in which, for a cylinder with the dimensions of the probe used, an approach is given to this asymptote within 3½ per cent at 10 seconds, and within 1½ per cent at 20 seconds. The linearity is valid up to about 10 minutes; for longer times the sample boundaries and finite length of the needle probe begin to affect seriously the approximation of

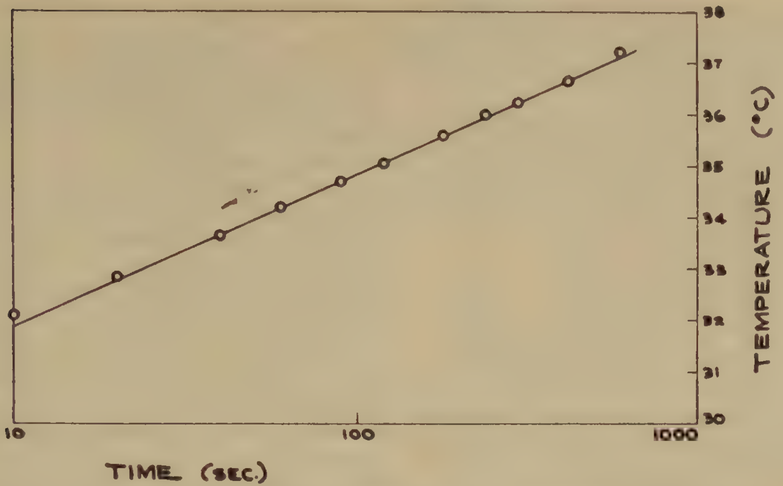

FIG. 2—Temperature versus time for a needle-probe measurement of *DWBG* 137.

an infinitely extended line source in an infinite medium.

A typical record for one of the needle-probe measurements is shown in Figure 2, where, with a 2-watt power input, the 10-minute time interval is found to be adequate for a determination of K. During this time, K is integrated over a sediment sample of approximately 2-cm radius, which approaches the radius of the core sample. Concurrently, there is a temperature increase at the needle probe of 5 to 7°C. As K has a small temperature coefficient—approximately that of water as determined by D. W. Butler (private communication) and verified by the authors—this temperature change would increase K by 1 to 2 per cent at the needle, and by lesser amounts at greater distances from the needle. No systematic increase of K with time has been noted during the measurements, and no corrections have been made for this effect. On the other hand, to correct the measurements of K to the near-freezing ambient temperature of the ocean bottom requires a reduction of 5 to 10 per cent of the measured value.

Thermal diffusivity—A knowledge of the thermal diffusivity, $\alpha = K/\rho C$, is required for the extrapolation of the records of temperature gradient obtained in oceanic heat-flow measurements. This has been determined for five samples of sediment material by independently measuring the conductivity K, the density ρ, and the water fraction by weight w. As the thermal capacity C depends largely upon the water content, and very little on the mineralogical composition of the solid fraction, C has been obtained from w in the manner described by *Bullard* [1954].

A plot of experimentally determined values

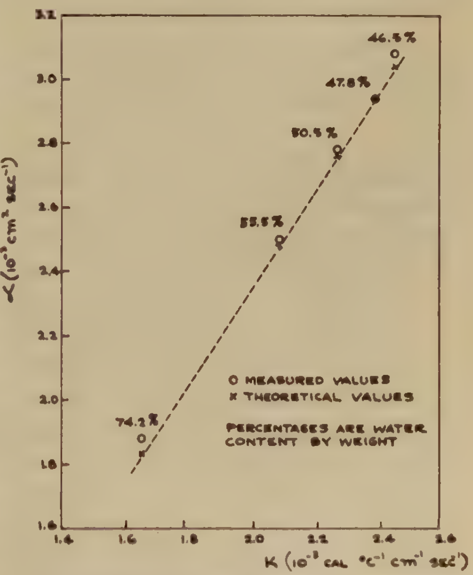

FIG. 3—Thermal diffusivity α versus thermal conductivity K of deep-sea sediments from the southeastern Pacific Ocean.

of α against K (Fig. 3) shows the relationship to be nearly linear for the range of measured values, suggesting that α might be determined simply from a knowledge of K.

If it is assumed that the sediments can be represented as solids in a fluid medium, it is then possible to determine a theoretical relationship between α and K. For example, the density may be written as

$$\frac{1}{\rho} = \left(\frac{1}{\rho_w} - \frac{1}{\rho_s}\right) w + \frac{1}{\rho_s} = \frac{w}{\rho_w}\left[1 + \frac{1-w}{w}\left(\frac{\rho_w}{\rho_s}\right)\right] \qquad (2)$$

Where ρ_w is the density of water fraction and ρ_s is the density of the solid fraction. Similarly, the heat capacity is given by

$$C = C_w w + (1 - w)C_s = wC_w\left[1 + \frac{1-w}{w}\left(\frac{C_s}{C_w}\right)\right] \qquad (3)$$

where C_w is the heat capacity of the water fraction and C_s the heat capacity of the solid fraction. From equations (2) and (3) the relation between α and K is given by

$$\frac{\alpha}{K} = \frac{1}{\rho_w C_w}\left[\frac{1 + \dfrac{1-w}{w}\left(\dfrac{\rho_w}{\rho_s}\right)}{1 + \dfrac{1-w}{w}\left(\dfrac{C_s}{C_w}\right)}\right] \qquad (4)$$

The following values have been used for the densities and specific heats:

ρ_w = 1.03 gm/cm³ (density of sea water)
ρ_s = 2.50 gm/cm³ (determined by plotting $1/\rho$ versus w for a series of deep-sea sediments from the Pacific and using the $1/\rho$ intercept as given in equation (2))
C_w = 0.94 cal/gm°C [*Sverdrup and others*, 1942, p. 61]
C_s = 0.18 cal/gm°C [*Bullard*, 1954]

With these values, equation (4) has been used to compute the theoretical values of α in Figure 3 from the corresponding measured values of K and w. The best-fitting least-squares linear relationship, which allows for interpolations of sufficient accuracy, is given by

$$\alpha = 1.53\,K - 0.70 \times 10^{-3} \qquad (5)$$

and shown as the dashed line. The agreement between the theoretical and experimental values is reassuring and lends strength to the suggestion that α can be predicted with sufficient accuracy from a knowledge of K.

Another method of determining α directly by the needle method is described by *Jaeger* [1958]. Use is made of the theoretical intercept on the ln t axis of the asymptote of T versus ln t, which is given by $Ba^2/4\alpha$. However, several objections arise in applying this method to the needle probe. Errors of conductivity, or slope of the line, of 2 per cent will produce errors in the intercept, and hence in α, of 10 per cent. The method of making successive graphical approximations to the true value of K suggested by *Jaeger* [1958] is not particularly applicable because the transient approach to a linear asympotote is not well determined for small t. This is because t is not measured accurately while T is changing rapidly. Another difficulty lies in the radius of the small probe (about 0.043 cm) which is known only with an accuracy of about 3 per cent. Finally, correction must be made for the finite conductivity of the probe by substracting a constant temperature from the experimental plot of T versus ln t. This correction has the effect of reducing the temperature at the sensing thermistor to that of the boundary of the cylindrical probe, thereby allowing a fit to the theory of the perfectly conducting cylinder. To determine this constant-temperature correction, it is necessary to measure several specimens of known K and α. Because of these difficulties and limitations we have concluded that it is simpler to utilize the former method of determining α. For our purposes, the accuracy of α obtained in this manner is adequate.

EXPERIMENTAL RESULTS AND COMPARISONS

In connection with an ocean floor heat-flow program carried out on several cruises of the research vessels of the Scripps Institution of Oceanography in the past few years, the authors used the needle-probe method for determining the thermal conductivity of many sediment cores from the Pacific Ocean floor. To establish the validity of the results, it was thought prudent to establish the accuracy of the technique. Good

TABLE 1—*Description of sediment sample*

Core number	Position		Ocean depth, m	Date taken	Description of core
	Latitude	Longitude			
**DWBG* 84	42°44′S	96°06′W	4700	1957 Dec. 15	Uniform dark brown zeolitic clay
DWBG 130	14°44′S	112°06′W	3120	1958 Feb. 11	Light brown clayey calcareous ooze, mottled
DWBG 135	11°42′S	109°43′W	3230	Feb. 14	Buff calcareous ooze
DWBG 137	09°53′S	110°41′W	2770	Feb. 15	Dark brown clayey calcareous ooze, color banding
DWBG 147-B	1°27′N	116°13′W	4000	Feb. 20	Mottled buff calcareous-siliceous ooze

**DWBG* refers to cruise, ship, and type of core taken: *DW*, DOWNWIND Expedition; *B*, S. F. BAIRD; *G*, gravity core.

agreement has been obtained on some samples measured by both the needle-probe and the steady-state methods. For example, bentonite clay had a K of (1.83 ± .02) × 10^{-3} cal/cm°C sec by the steady-state method, and (1.82 ± .03) × 10^{-3} by the needle probe. An additional check was made by molding a cylinder of solid naphthalene, similar in shape and size to a sediment core sample, around the needle probe. This gave a K of (.805 ± .008) × 10^{-3}cal/cm°C sec which compares favorably with the value of .804 × 10^{-3} listed in the *International Critical Tables* [1929].

A more extensive check was made by selecting five sediment samples obtained during the IGY DOWNWIND cruise to the southeastern Pacific Ocean for comparison of the needle-probe steady-state methods. Table 1 gives a brief description of the sediment cores from which the samples were selected. Conductivities were first determined by the needle-probe method in the laboratory in the same way as was done aboard ship. These various samples were then sent to three separate laboratories for independent steady-state measurements of thermal conductivity. When the core samples were returned they were again measured by the transient-state method. The results are summarized in Table 2. The first column gives the shipboard determination made by the needle-probe technique immediately after the cores were brought aboard. Shipboard measurements were made

TABLE 2—*Thermal conductivities*

Core number	K, 10^{-3} cal/°C cm sec					
	Shipboard	Lab *A* (before)	Lab *B*-1	Lab *B*-2	Lab *B*-3	Lab *A* (after)
DWBG 84	1.63	1.65	1.66	1.65	1.70	...
DWBG 130	2.33	2.38	2.53	2.6	2.28	2.33
DWBG 135	2.35	2.26	2.53	2.5	...	2.29
DWBG 137	2.14	2.08	2.13	1.95	1.98	2.07
DWBG 147-B	2.07	2.44	2.44	...	...	2.44
Estimated accuracy, %	∓3–4	∓3–4	∓4–5	∓4–5	∓3	∓3–4

three to five months prior to the laboratory determinations. Lab-*A* measurements are the needle-probe values obtained by the authors. The 'before' and 'after' values were made in an attempt to determine the effects of shipment and aging during steady-state measurements. Labs *B*-1, *B*-2, and *B*-3 refer respectively to the steady-state measurements on the same sediment samples by A. Beck, (University of Western Ontario, London, Canada), E. Robertson, (Geophysics Lab., USGS, Silver Spring, Maryland), and E. Ratcliffe, (National Physical Lab., Teddington, England). The need for measuring the conductivity as soon as possible after a core is retrieved is emphasized by these results. Changes in conductivity up to 20 per cent are possible in relatively short times because of evaporation and gravity settling in the core samples. Estimates of the accuracy of the needle-probe determinations were derived from the largest variations found on individual samples, and estimates of the accuracy of the steady-state measurements were provided by the respective investigators.

The water content and specific gravities were determined along with the thermal conductivities of the five samples. These values are given in Tables 3 and 4. Lab *B*-1 did not measure the water content of the samples, and water had to be added to *DWBG* 135 because of accidental dehydration during shipment. This may account for some of the discrepancy of the needle-probe measurements for this sample. Lab *B*-2 measured the densities and water contents before and after measurements of thermal conductivity were made. Although the water contents and densities were determined in slightly different ways by each laboratory, Tables 3 and 4 show that these parameters were sufficiently constant for comparisons of thermal conductivity to be made.

TABLE 3—*Water-content determinations*

Core number	Water content, percentage of wet weight			
	Lab *A*	Lab *B*-2 Initial	Lab *B*-2 Final	Lab *B*-3
DWBG				
84	74.3	78	76	71
130	47.8	48	46	43
135	50.5	51	50	...
137	55.5	56	53	56
147-B	46.5	...	...	...

TABLE 4—*Density determinations*

Core number	Specific gravity				
	Lab *A*	Lab *B*-1	Lab *B*-2 Initial	Lab *B*-2 Final	Lab *B*-3
DWBG					
84	1.19	1.19	1.14	1.17	1.17
130	1.50	1.50	1.51	1.60	1.56
135	1.45	1.42	1.48	1.58	...
137	1.39	1.41	1.37	1.43	1.36
147-B	1.50	1.51	...	...	...

Comparative results for the transient and steady-state techniques show good agreement, except perhaps for *DWBG* 130 and 135. Independent steady-state measurements by Lab *B*-1 and Lab *B*-2 for *DWBG* 130 and 135 were consistent with each other but were about 10 to 12 per cent higher than the needle measurements. This suggests a possible systematic error between the two types of measurements. On the other hand, the Lab *B*-3 determination is consistent with the needle measurement for *DWBG* 130. One explanation of the discrepancy is strongly suggested by the fact that during shipment these two specimens showed a large water separation from the solid fraction of sediment material. This was probably due to an unstable water saturation and high permeability, the water separation occurring with the disturbance and time involved during the shipment.

Successive determinations of needle conductivity at the same place on *DWBG* 135, made after the steady-state measurements, gave increasingly higher results. The magnitude of these approached the steady-state values. This is probably due to a migration of water by gravity, or perhaps more likely because of migration in the vapor phase away from the warm needle toward the cooler parts of the core; either would tend to increase the measured thermal conductivity. Significant errors of this effect for a single needle measurement have not been noted. This effect may be larger for a steady-state measurement, since a longer time is involved during the measurement. Lab *B*-2 actually noticed an increase in conductivity with time during some of the measurements. The effect could also be due to heat losses from the apparatus, which would be expected to be larger for the steady-state apparatus than for the needle probe. However, this effect was not noticed for all samples, and it is more likely a property of a particular type of sediment.

CONCLUSIONS

The comparative results between the needle and steady-state determinations are nearly all within the errors estimated for the respective measurements. The error of 3 to 4 per cent for the needle measurements has been estimated from the combination of possible errors in calibration and random errors on repeated measurements. Random errors are probably only 1 or 2 per cent on repeated measurements, and careful calibration can probably reduce the systematic errors to even lower values. Care must be taken on repeated measurements that the sediment material in the immediate vicinity of the needle probe does not dehydrate and thereby increase the the apparent conductivity. It is concluded that the needle method of determining thermal conductivity of deep-sea sediments is as accurate as steady-state methods, and it has the advantages of being much more quickly made and more conveniently used on board ship.

The method also lends itself to the measurement of thermal conductivity *in situ* on the ocean floor at the same time that a temperature gradient measurement is made; this would largely eliminate the difficulties and uncertainties involved in raising a sediment sample to the surface.

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REFERENCES

BECK, A., A steady-state method for the rapid measurement of the thermal conductivity of rocks, *J. Sci. Instr.*, *34*, 186–189, 1957.

BEUTTNER, K., A small portable meter for soil heat conductivity and its use in the O'Neill test, *Trans. Am. Geophys. Union*, *36*, 827–830, 1955.

BULLARD, E. C., The flow of heat through the floor of the Atlantic Ocean, *Proc. Royal Soc. London A*, *222*, 408–429, 1954.

BULLARD, E. C., A. E. MAXWELL, AND R. R. REVELLE, Heat flow through the deep sea floor, *Advances in Geophys.*, *3*, 1956.

D'EUSTACHIO, D., AND R. E. SCHREINER, A study of a transient heat method for measuring thermal conductivity, *Trans. Am. Soc. Heat. and Vent. Engr.*, *58*, 331–342, 1952.

INTERNATIONAL CRITICAL TABLES, vol. 5, McGraw-Hill Book Co., New York, 1929.

JAEGER, J. C., Conduction of heat in an infinite region bounded internally by a circular cylinder of a perfect conductor, *Australian J. Phys.*, *9*, 167–179, 1956.

JAEGER, J. C., The measurement of thermal conductivity and diffusivity with cylindrical probes, *Trans. Am. Geophys. Union*, *39*, 708–710, 1958.

LACHENBRUCH, A. H., A probe for measurement of thermal conductivity of frozen soils in place, *Trans. Am. Geophys. Union*, *38*, 691–697, 1957.

MASON, V. V., AND M. KURTZ, Rapid measurement of the thermal resistivity of soil, *Elec. Eng.*, *71*, 985–992, 1952.

MAXWELL, A. E., *The outflow of heat under the Pacific Ocean*, Ph.D. dissertation, Scripps Inst. Oceanog., 1958.

SVERDRUP, H. U., M. W. JOHNSON, AND R. H. FLEMING, *The Oceans*, Prentice-Hall, Inc., 1087 pp., 1942.

VAN DER HELD, E. F. M., J. HARDEBOL, AND J. KALSHOVEN, On the measurement of the thermal conductivity of liquids by a non-stationary method, *Physica*, *19*, 208–216, 1953.

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Some Geomagnetic Phenomena associated with Nuclear Explosions

The three International Geophysical Year stations operated in the central Pacific by the Scripps Institution of Oceanography have consistently recorded magnetic disturbances following, and apparently caused by, the various nuclear tests conducted by the British in the vicinity of Christmas Island. This fact is particularly interesting because, unlike the American bomb which was exploded in the ionosphere over Johnston Island on August 1, 1958, producing auroral and magnetic effects over a large area of the Pacific[1], the British tests are believed to have occurred at relatively low altitudes in the lower atmosphere.

Fig. 1 shows magnetograms for the explosion of April 28, 1958, and Fig. 2 the positions of the observing stations relative to the shot point, which was stated to have been within ten miles of 1° 40′ N., 157° 15′ W. The altitude has not been disclosed, but official reports indicate that the device was dropped by a *Valiant* jet bomber, and it may be supposed that the height of detonation was substantially less than the ceiling of about 60,000 ft. for that class of aircraft.

The pronounced anomalies in Z and D, which reach a maximum at Jarvis and Fanning between 12 and 15 min. after the event and at Palmyra about 10 min. later, are similar in character to those which followed other tests, and we have no doubt that they are directly related to the nuclear explosion. We have examined magnetograms from the nearest magnetic observatories outside the immediate area, that is, Apia, Guam and Honolulu, but have not found any magnetic effects that we can positively identify with this or with any other of the British tests. This is surprising, because Apia and Honolulu are only about three times as far as Palmyra from Christmas Island.

The disturbances recorded at our three stations have several features in common. They begin quite suddenly after a delay of several minutes (rather longer at Palmyra than at the other two stations), they move in the same relative phase and they persist for about half an hour, but perhaps the most striking feature of the magnetograms is the absence of any observable disturbance in H corresponding to the major disturbance in Z and D (though an unusual, and probably related, type of local disturbance in H

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at Palmyra commenced about 26 min. after the event and lasted for about 20 min.). The absence of an *H* component would be explained if the phenomenon involved horizontal currents parallel to the magnetic meridian, and in this connexion it may be noted that the Earth's magnetic field is very nearly horizontal throughout the area. More generally, possible mechanisms for producing such disturbances include :

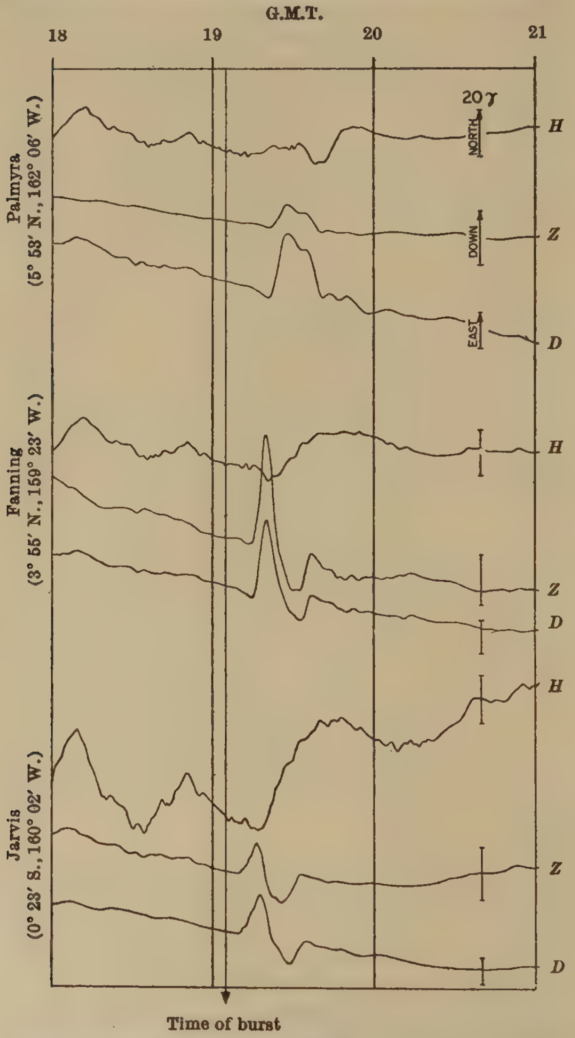

Fig. 1. Magnetograms for the Christmas Island nuclear explosion of April 28, 1958

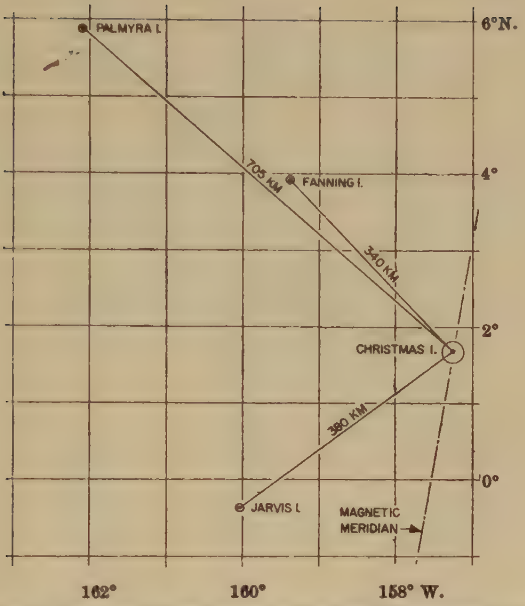

Fig. 2. Positions of the Scripps International Geophysical Year stations relative to the shot point near Christmas Island

(*a*) the motion of charged particles, in certain circumstances controlled by the Earth's magnetic field ; (*b*) the modification of existing ionospheric currents through displacement of the conducting medium or changes in conductivity ; (*c*) the mechanical disturbance of a magnetic field frozen into a mechanically disturbed conducting medium. To these must be added the secondary effect of induction within the Earth.

In order to bring out more clearly the vector characteristics of the disturbances, diagrams have been constructed showing the time variation of their projections in various planes, measured as the departure of the observed field from an assumed smooth background (represented by the origin of the vector diagram). Fig. 3*a* shows diagrams for the vertical plane perpendicular to the magnetic meridian. The explanation of the large time delay at Palmyra is now seen to be that, although the vectors at all three stations reach peak values in one direction between 12 and 16 min. and in the opposite direction between 23 and 27 min., the directions and amplitudes of the two peaks at Palmyra are reversed.

Fig. 3*b* shows the corresponding diagrams for the Johnston Island explosion of August 1, 1958. Having

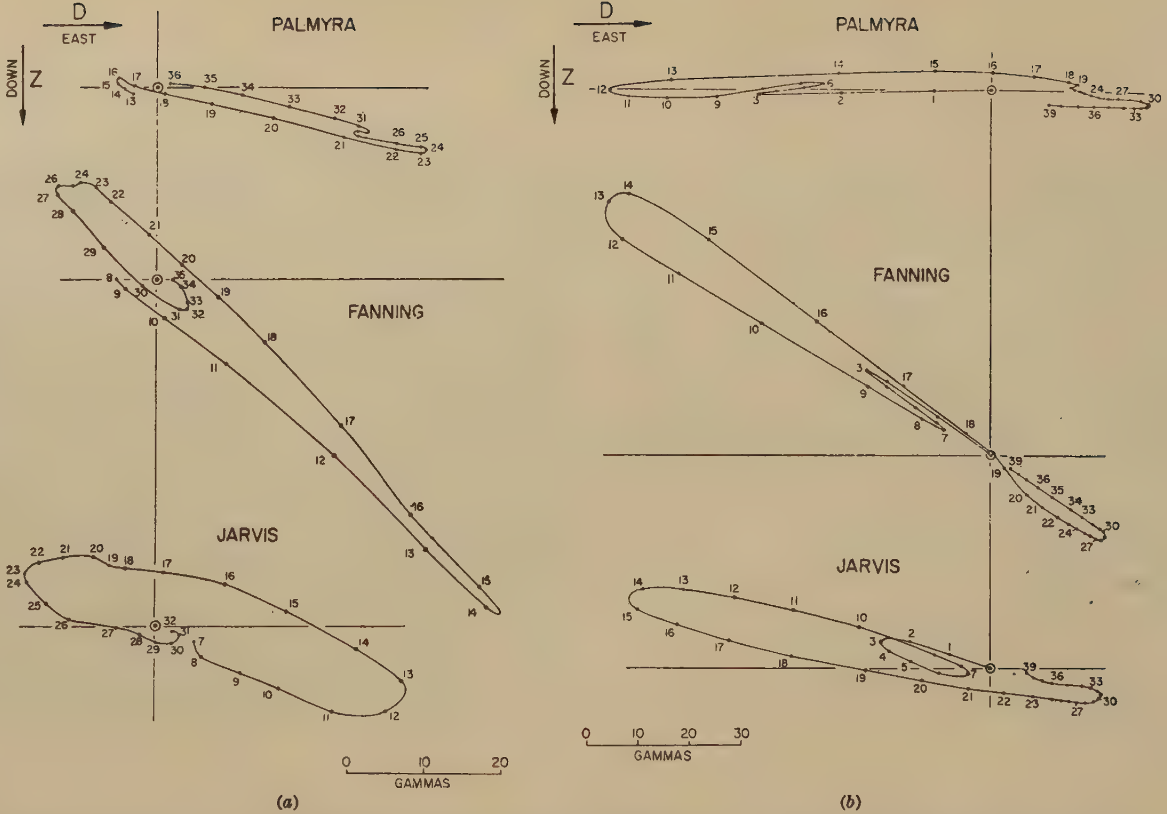

Fig. 3. Vector diagrams of the disturbance in the vertical plane perpendicular to the magnetic meridian for (*a*) the Christmas Island explosion of April 28, 1958; (*b*) the Johnston Island explosion of August 1, 1958. The small figures indicate the time in minutes after the event.

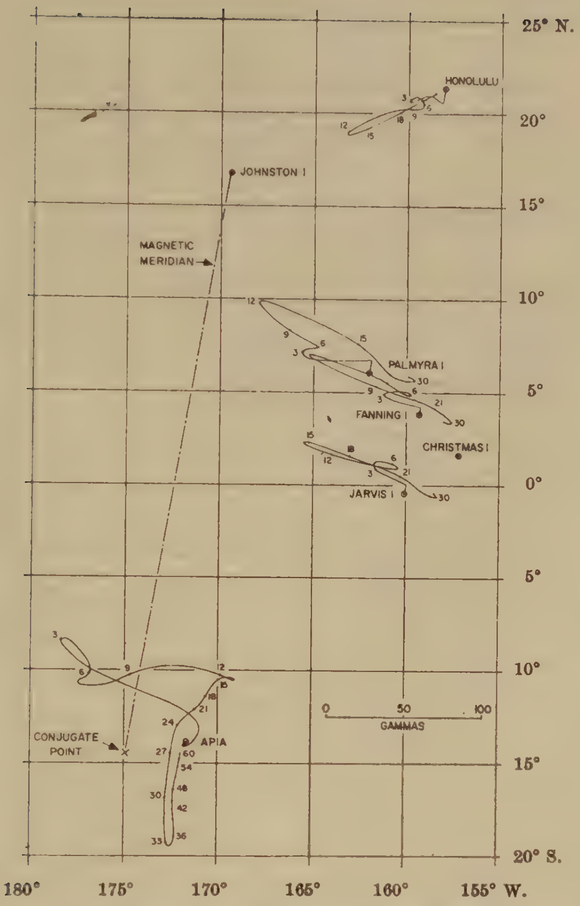
25° N.
20°
15°
10°
5°
0°
5°
10°
15°
20° S.
180°
175°
170°
165°
160°
155° W.
HONOLULU
JOHNSTON I
MAGNETIC MERIDIAN
PALMYRA I
FANNING I
CHRISTMAS I
JARVIS I
CONJUGATE POINT
APIA
0
50
100
GAMMAS

Fig. 4. Vector diagrams of the disturbance in the horizontal plane for the Johnston Island explosion of August 1, 1958. The small figures indicate the time in minutes after the event

regard to the altogether different geographical positions and altitudes of the two events, the similarity of the two sets of diagrams is remarkable. However, unlike the Christmas Island explosion, the Johnston Island event produced changes in H comparable in magnitude with those in D and Z. Fig. 4 shows vector diagrams of the disturbance in the horizontal plane, plotted to show the relative directions of the magnetic vector, Johnston Island and the conjugate point (taking Elliot and Quenby's position[3]) at each station. This event produced effects not observed in connexion with the Christmas

Island tests, for example, an instantaneous change in H of about 10 gammas.

It is clear from the complicated nature of the Johnston Island disturbance, and from the extent to which it resembled the disturbance produced by the dissimilar Christmas Island event, that no simple explanation of the magnetic phenomena is to be expected; it is probable that several distinctly separate mechanisms are involved.

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[1] Cullington, A. L., *Nature*, **182**, 1365 (1958).

[2] Elliot, H., and Quenby, J. J., *Nature*, **183**, 810 (1959).

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Resonance Absorption and Molecular Crystals. II. Benzene†

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Thermal oscillations in molecular solids are of two distinct classes: lattice vibrations and atomic vibrations within each molecule. These two vibrational modes can overlap in frequency and "resonate." This resonance leads to lengthy relaxation times manifested as unusually high acoustic absorption, a phenomenon termed resonance absorption. In order to study resonance absorption in solid benzene a method was developed for growing single benzene crystals of average linear dimension, 10 cm. At the acoustical frequency 10 mc, absorption in single benzene crystals is found to be 0.24 cm^{-1}; at 6.4 mc the value is 0.09 cm^{-1}. This excessively high absorption (10^4 higher than in crystalline quartz) was quantitatively predicted from available molecular constants by a theory given previously. A partial list of compounds is given in which resonance absorption is predicted to be the dominant absorption mechanism.

INTRODUCTION

A MOLECULAR crystal exhibits two classes of thermal oscillation: those in which each molecule vibrates as a whole about its lattice position, termed the acoustical branch, and the internal vibrations of the atoms comprising a molecule, termed the optical branch. In many crystals these two vibrational modes overlap in frequency, leading to resonance.

Previous work,[1] hereafter referred to by the designation I, has shown that resonance can result in unusually high acoustic absorption. High absorption results from the relatively slow transfer or exchange of energy between lattice and internal vibrations. Just as in weakly coupled mechanically resonant systems, the transfer energy at resonance is large, but the rate of transfer is slow, particularly close to resonance. The phenomenon is some respects resembles the familiar relaxation absorption observed in gases and liquids, but the latter arises from transfer of energy by collision, whereas the present phenomenon requires near frequency coincidence of two vibrational states; hence the term, *resonance absorption*. It should be emphasized that this resonance phenomenon is not associated with acoustical frequencies but rather with the extremely high frequency thermally excited vibrational modes within the crystal.

It was shown in I that the rate with which energy oscillates between the two vibrational systems determines the acoustical absorption; a low transfer frequency leads to large acoustic absorption. Stated in another manner, whenever the oscillator coupling is small, or the intermolecular binding forces weak, absorption will be high. Conversely, in highly absorbing crystals the Lennard-Jones molecular constants, ϵ and r_0, will be found to be small and the intermolecular spacing large.

Tables of the Lennard-Jones constants suggest that many organic compounds should exhibit resonance absorption in the solid state. One of these, benzene, was selected for initial study because of the wide variety of thermodynamic data available for this compound. Although benzene is a liquid at room temperature it has a relatively high melting point (5.5°C) which makes its study in the solid state possible without unusual techniques. However, it is necessary for acoustic observations to be made on a single crystal rather than on the polycrystalline state, in order to eliminate contributions to absorption from friction and scattering at crystal boundaries, fractures, and at other imperfections. For this reason a large single crystal of benzene was grown for the purpose of the acoustic observations. The following sections describe the method of preparation of the crystal and observations of the acoustic absorption.

GROWTH OF MONOCRYSTALLINE BENZENE

As in the case of nearly all organic compounds, molecular binding forces in benzene are relatively weak (its binding forces are largely van der Waals' forces). Consequently crystalline benzene is a fragile substance incapable of supporting severe thermal stresses. The conventional technique for crystal growth in which heat flows through the external crystal surface introduces far too many stresses and could not be utilized for benzene.

The schematic diagram given in Fig. 1 illustrates the method whereby unsupported thermal strains were avoided in crystal growth. Instead of the usual method of crystallization from the liquid, whereby heat is extracted from the external surfaces, heat is extracted from within. The coldest exposed region is the tip of a heavy copper rod on which the seed is placed. Hence the exterior growing surface is always warmer than the central region and thermal stresses are compressive rather than in tension. In practice the copper tip was attached directly to the refrigeration coils and operated in the vicinity of 0°C. The air temperature in the refrigerator was accurately controlled by means of heaters and thermostats at a constant temperature in the vicinity of 3°C. In addition a small amount of

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† This work received support from the Bureau of Ships, Navy Department. Contribution from the Scripps Institution of Oceanography, New Series. 1106

[1] L. Liebermann, Phys. Rev. 113, 1052 (1959).

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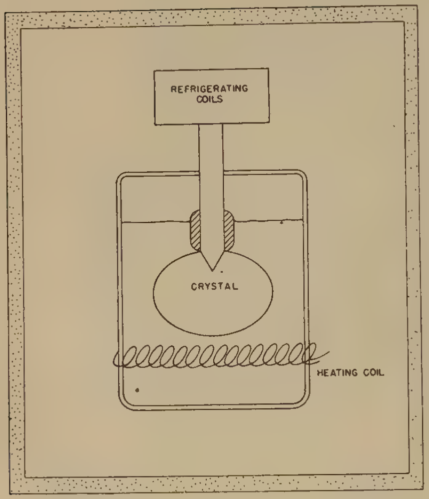

FIG. 1.

heat was introduced at the surface of the glass container of liquid benzene by means of a concentric heater coil. This had the function of generating concentric convective stirring.

By means of this apparatus a single crystal of benzene of approximate dimensions 10 cm×5 cm×5 cm could be grown in one week. Optical examination with polarized light was used during the period of crystal growth to discern possible defects. Reagent grade benzene was used which had been previously outgassed. The glass benzene container was sealed both to prevent ingress of air and egress of benzene vapor.

A single crystal of benzene is colorless and perfectly transparent. Its crystal symmetry is orthorhombic, space group *Pbca*; because of its symmetry it grows with a nearly hemispherical surface, no crystal planes being visible. Even in the solid state the vapor pressure is relatively high and the crystal rapidly sublimates unless kept in a sealed container.

ACOUSTICAL ABSORPTION MEASUREMENTS

The extraordinarily large acoustic absorption resulting from resonance is readily observed with conventional techniques. Direct observation of the amplitudes of 10-μsec pulses was used in two methods: In one set of measurements the pulse amplitude was measured as a function of range by successively melting the crystal, thus diminishing the range. An alternative method was used in which the crystal length remained fixed and absorption deduced from the amplitudes of successive reflections from the end faces. The latter method presupposes the reflection coefficient is sufficiently high that it can be taken as unity. Absorption in benzene was found to be sufficiently high that the reflection method gave adequate precision, end losses being negligible. This method was preferred because it avoided destruction of the crystal.

Measurements were conducted at two frequencies, 6.4 and 10.7 mc. Two barium titanate wafers 1 cm in diam, 1 mm thick, were used as transmitter and receiver. Both frequencies could be observed without changing transducers. In order to make accurate absorption measurements it is necessary that the external crystal faces on which the transducers are placed be machined perfectly plane and parallel. This condition was achieved by melting the benzene crystal in a special jig. Maximum usable length between these faces was 6 cm.

Although the diameter of the transducer was very large compared to acoustic wavelengths, plane wave distortion resulting from diffraction was not negligible and introduced an additional spurious attenuation for which a correction was made. An approximate value for the apparent attenuation resulting from diffraction[2] is 1 db per a^2/λ where a is the transducer radius. At the 6.4-mc frequency this correction amounted to $\alpha=0.016$ cm^{-1}; at 10.7 mc the correction was $\alpha=0.0097$ cm^{-1}.

The observed acoustic absorption in benzene, corrected for diffraction, has the following values:

$$\alpha=0.09 \text{ cm}^{-1} \text{ at } 6.4 \text{ mc.}$$

$$\alpha=0.24 \text{ cm}^{-1} \text{ at } 10.7 \text{ mc.}$$

The ratio of these two absorptions is 2.7. The ratio of the square of the frequencies, $(10.7/6.4)^2=2.8$; hence, absorption varies as the square of the frequency, at least in this region. The velocity determined from pulse measurements on a cathode ray oscillograph gave 3.1×10^5 cm/sec at 0°C. Absorption was found to be practically independent of temperature to -58°C.

The foregoing values for acoustic absorption are exceedingly high for nonmetallic crystals, particularly for single crystals. For example, a good estimate of the absorption in monocrystalline quartz[3] is $\alpha=10^{-5}$ cm^{-1} at 10 mc, or nearly *four orders of magnitude less attenuation.* As a check on the experiment, measurements on a sample of ice cut from a block of commerical ice, of rather poor optical quality, yielded $\alpha=0.04$ cm^{-1} at this frequency, an order of magnitude lower, in spite of its many imperfections and polycrystalline state. In addition, the absorption in crystalline quartz and in most solids is known to increase in proportion to the frequency whereas present observations indicate that absorption in crystalline benzene increases as the *square* of the frequency. In the next section this anomalous absorption evidenced by solid benzene is interpreted quantitatively with the aid of the theory presented in I.

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[2] Seki, Granato, and Truell, J. Acoust. Soc. Am. 28, 230 (1956).

[3] W. P. Mason, *Physical Acoustics and the Properties of Solids* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1958), p. 288.

THEORETICAL INTERPRETATION

It was shown in I that the familiar formula for relaxation absorption,

$$\alpha=\frac{1}{2V}\frac{c_p-c_v}{c_p}\frac{c'}{(c_p-c')}\frac{\omega^2\kappa}{(\omega^2+\kappa^2)}, \tag{1}$$

applies equally well to resonance absorption. In resonance absorption, the quantity κ is interpreted as the "beat" frequency between lattice and internal vibrations; c' is the specific heat of the internal vibration. The formula for κ given in I is

$$\kappa=\frac{9A^2(kT)^3N^4}{16h\nu_{01}m_{01}\nu_m{}^7(4\pi^2M)^3}. \tag{2}$$

The quantities m_{01} and ν_{01} are the effective mass and frequency of the internal vibrator; M is the molecular weight; ν_m is the Debye frequency available from specific heat data; h is, of course, Planck's constant. The quantity A is a measure of the strength of the intermolecular binding forces; it is a function of ϵ and r_0, the Lennard-Jones parameters, available in tables.

TABLE I. Numerical constants for benzene.

ϵ (Lennard-Jones parameters)[a]	6.15×10^{-6} erg
r_0	5.27×10^{-8} cm
d (intermolecular spacing)[b]	5.03×10^{-8} cm
A (ϵ,r_0,d) (coupling parameter)	1.73×10^{20} g cm^6/sec^2
ν_m (Debye frequency)[c]	3.1×10^{12} sec^{-1}
ν_{01} (internal vibrational frequency)[d]	1.21×10^{13} sec^{-1}
M (molecular weight)	78.11 g
m_{01} (apparent internal vibrating mass)	23 g
T (temperature)	273°K

[a] Hirschfelder, Curtis, and Bird, *Molecular Theory of Gases and Liquids* (John Wiley & Sons, Inc., New York, 1954), p. 1112.

[b] E. R. Andrew and R. G. Eades, Proc. Roy. Soc. (London) **A218**, 537 (1953).

[c] Lord, Ahlberg, and Andrews, J. Chem. Phys. 5, 649 (1937).

[d] R. C. Lord, Jr., and D. H. Andrews, J. Phys. Chem. 41, 149 (1937).

The constants required to calculate κ for benzene are given in Table I. Substitution in (2) leads to $\kappa=10^9$/sec; this is a relatively low transition frequency for molecular processes. The predicted acoustic absorption from (1) utilizing this transition frequency is approximately 0.5 cm^{-1} at 10^7 cps; this is to be compared with the above observed value of 0.24 cm^{-1}. The agreement is excellent considering the many uncertain molecular parameters involved. The agreement of the lower frequency is equally good, for it is seen that the theoretical prediction of (2), that absorption should depend on the square of the frequency, is verified experimentally. Clearly the major source of acoustic dissipation in solid benzene originates in resonance absorption.

TABLE II. Compounds which are predicted to exhibit high resonance absorption.

	Lennard-Jones ϵ (°K)	Parameters r_0 (A)	Melting point (°C)
Benzene	440	5.27	5.5
Acetylene	185	4.22	−82
Ethane	230	4.42	−172
Butane	410	5.00	−135
Carbon disulfide	488	4.4	−108
Chloroform	327	5.4	−63
Methylene chloride	406	4.76	−97

DISCUSSION

It would be of considerable interest to search for other molecular crystals which also exhibit strong resonance absorption. Such substances would be characterized by a small value for κ, the transference frequency given in (2). The sensitive parameters in this equation appear to be A, a measure of the intermolecular binding forces; ν_m, the Debye frequency; and M, the molecular weight. However, the Debye frequency is related to the molecular weight and the combined effect of these two parameters may not be important. Probably of considerable importance for strong absorption is the requirement that A be small, or the binding forces weak; this implies that the Lennard-Jones parameters, ϵ and r_0, are small.

Table II gives the Lennard-Jones parameters for some relatively simple hydrocarbons selected because their constants are smaller than those for benzene (included for comparison). These compounds appear likely to exhibit high acoustic absorption provided resonance occurs, i.e., that the internal frequency, ν_{01}, is not appreciably greater than $3\nu_m$.

It is to be emphasized that calculation of resonance absorption is highly dependent on precise knowledge of intermolecular forces. Unfortunately, present knowledge of these forces, even in well studied molecules, e.g., benzene, is relatively crude. Conversely, acoustical measurements could well lead to important contributions to the understanding of these fundamental molecular properties.

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*BIOASSAY OF ORGANIC MICRONUTRIENTS IN THE SEA**

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SCRIPPS INSTITUTION OF OCEANOGRAPHY

Communicated by Carl L. Hubbs, August 14, 1959

Introduction. It has often been stated[1] that oceanic production is limited by the quantity of phosphate in the marine environment. The best data available indicate that the concentration of phosphate in the water off the coast of California is about ten times as high as that found in the English Channel. Yet the total productivity

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of the English Channel area has been consistently greater than that found off our coast. Why is it that even in the presence of sufficient concentrations of the essential inorganic nutrients, our Pacific coast is barren relative to that of an area poor in those same inorganic substances? Although it is possible that variability in the phosphorus-nitrogen ratio might in part account for this lower production, it would seem more reasonable to explore the situation further in terms of other limiting substances. As a result of a number of independent observations over a period of years, attention has been focused on organic, rather than on inorganic substances as limiting agents. The literature on the subject has been reviewed by Lucas,[2] Provasoli,[3] and Margalef.[4] I shall cite only a few of the pertinent papers, dealing with the implication of organic micronutrients in marine biology. Historically, Allen[5] in 1914 observed that in the absence of either natural sea water or an extract of *Ulva* (a marine alga), the diatom *Thalassorsira gravida* failed to grow in his artificial sea water. In some more recent experiments with algae, Harvey[6] has found that *Ditylium brightwelli*, another diatom, cannot be grown continuously even in natural sea water enriched with nitrate, phosphate, and iron. He suggested that accessory substances, probably of organic nature, are required for continuous production. As more and more marine algae are being cultured in the laboratory, in defined media and in the absence of bacteria, some of the organic compounds required for their growth are being uncovered. Lewin[7] has demonstrated an absolute requirement for cobalamin by a marine *Stichococcus*, and Sweeney[8] has found that the same vitamin is necessary for the growth of *Gymnodinium*. Droop[9] has found requirements for both vitamins B_{12} and B_6 in a variety of algae. Galactose, a monosaccharide, has been shown by Collier[10] to stimulate filtering rate in oysters. Loomis[11] reported that the feeding response in Hydra is triggered by glutathione. Wilson[12] has postulated that the basis for the discontinuous distribution of bottom communities of invertebrates may reside in some minute quantities of organic material, since exhaustive analysis of physical and inorganic chemical conditions fails to yield the answers to why the organisms aggregate. The red tide, a profuse growth of marine algae, has been shown to be markedly stimulated by vitamin B_{12}. The occurrence of red tides has been correlated with the presence of vitamin B_{12} in near-shore waters and also with reduced salinities resulting, from rain run-off from the land. Even though not absolutely required, certain organic substances have been found to stimulate growth. Lewin,[13] for example, has demonstrated that a marine alga, *Prasiola stipitata*, can grow in the absence of organic material, but is markedly stimulated by the presence of organic nitrogen.

Wilson's observations[12] on the distribution of marine invertebrates certainly suggest that some soluble or small particulate organic substance may be involved, and such phenomena as plankton succession and initiation of plankton blooms may be explainable on the basis of growth factors, antibiotics, and other stimulatory and inhibitory compounds. Many attempts have been made to correlate the patchy distribution of plants and animals, bloom initiation, and bloom succession with inorganic chemicals, light and salinity, but the data are far from conclusive. Variations in the inorganic consitutents do not seem adequate to cause the marked variations in the biological phenomena involved. For these reasons, it seemed reasonable to attempt to establish a method that would detect small amounts of organic materials in sea water and would possibly indicate a basis for these dynamic processes.

A number of attempts have been made to isolate and characterize organic materials from sea water by biochemical techniques, but most of these attempts have been cumbersome and time-consuming. Moderate success was encountered by Provasoli and Pintner,[14] and Johnston,[15] in extracting and concentrating organic material, but it seems likely that a biological assay would be more sensitive than even the most refined biochemical techniques, and might detect many substances that would be missed entirely by those techniques. One of the most sensitive and useful techniques in biochemistry, chromatography, is limited in its application, since its use requires that the water first be desalted, or that the organic substances be adsorbed on some agent, then eluted and concentrated prior to chromatography. The high salt concentrations in sea water preclude direct chromatography.

The response of biochemically deficient mutant strains of bacteria to their specific metabolites suggested that it might be possible to utilize these mutants for a qualitative, and perhaps even quantitative, bioassay. They respond to very low concentrations of biochemicals and are relatively specific in their response. Attempts to train *Escherichia coli*, in which many mutants are already in culture, to grow in sea water were impractical. After as many as fifteen transfers, only sporadic growth was obtained. Therefore, a number of marine bacteria were screened for desirable characteristics, and *Serratia marinorubra* was selected as the most suitable organism.

Materials and Methods.—*Serratia marinorubra*[16] is a gram-negative coccobacillus, 0.3 by 0.6 microns in size, and is characterized by its red pigment. It grows well in a medium composed of inorganic salts with glycerol as the sole source of energy. The organism has a broad salt tolerance: it grows in both fresh water and three-times concentrated sea water. Stock cultures are maintained on slopes containing 1.5 per cent agar, 2.0 per cent glycerol, and 0.2 per cent peptone in sea water. This nutritionally independent or "wild" type stock is labeled SIO.

Mutant cultures with requirements for biochemical compounds have been induced by ultraviolet light, and isolated by a variety of techniques. The organisms may be grown either in liquid medium or on agar surfaces prior to irradiation. If grown on agar surfaces, the organisms are picked with a wire loop and suspended in sterile water for the irradiation. Those grown in liquid medium are washed several times by centrifugation-decantation, and the final pellet suspended in sterile water. The suspension resulting from either of these methods is then visually adjusted to approximately 10^8 organisms per ml turbidity and 7 ml is delivered into a sterile petri plate. This volume gives a relatively uniform 1-mm-thick layer in the Petri plate. The plate is placed on a ring-stand at a distance of 50 cm from the ultraviolet source and is treated for various times. During irradiation, the organisms are agitated in the suspension by a small stirring motor, which is attached to the ring-stand and which has its shaft deliberately thrown out of center. This imparts a vibrational motion to the ring-stand, and very effectively agitates the bacterial suspension, thus ensuring that the bacteria receive a random and relatively uniform dose of irradiation per cell. We have found best production of mutants in the range of 0.01 to 0.001 per cent survival, and this is obtained by exposing the suspension for periods of 60 to 80 seconds. The approximate dose of ultraviolet delivered in 60 seconds is 1000 ergs/mm.[2] After irradiation, several methods are routinely used to recover the mutants. The treated suspension may be plated on agar medium containing complete enrichments, so that all mutant and nutritionally independent cells will rapidly attain a profuse colonial growth. By taking advantage of the Lederberg and Lederberg[17] replica plating technique, these colonies can be transferred to a sterile velvet pad and in turn from that imprinted on minimal and complete media. Those colonies which grow on complete but not minimal medium have lost the ability to synthesize some biochemical necessary for their growth and are transferred with a wire loop to an agar slope for later analysis. Another method for recovery of mutants from the irradiated suspension is to plate the treated cells on agar medium which contains a limiting concentration of enrichment. The nutritionally independent cells surviving the irradiation will grow and produce normal-sized colonies, while any biochemically deficient mutants will grow only until they have exhausted the local environment of the small concentration of their specific substrate which has been added, at which point growth will be arrested. By taking advantage of the resulting difference in colony size, the small colonies can be picked with a wire loop and tested by inoculating complete and minimal medium with the suspected mutant, as above.

When they have been isolated and are in culture on agar-slope tubes, the mutant stocks may be tested for their specific requirements. The commonly recognized biochemical constituents of most microbial media have been made up into pools for convenience in testing. These pools are as follows:

Pool 1. Essential amino acids.
Pool 2. Non-essential amino acids.
Pool 3. Purines and pyrimidines (bases, ribosides, and ribotides).
Pool 4. Vitamins (a total of 22 vitamins in 50 per cent ethanol).

Agar plates are prepared which contain complete medium, minimal medium, and minimal medium containing the above pools, one in each plate. This gives a total of six plates, and the mutant is streaked with a wire loop on the surface of each of these six plates. The complete medium plate is a viability control, and the mutant grows thereon. The minimal-medium control is used for a reverse mutation check, for if the mutant is stable, no growth should be observed. If the mutant grows on one of the pools, then it is a simple matter to check the individual compounds comprising that pool for their ability to satisfy the requirement of the mutant. For the purpose of our bioassay system, mutants that do not respond to one of the pools are not tested further but are held separate for other work. Mutants that do respond to a pool are further tested as follows: A heavy suspension of the mutant is spread uniformly over the surface of a minimal-medium plate. By definition, the mutant will not grow on this plate in the absence of added biochemicals. Now crystals of each of the biochemical compounds comprising the pool are dropped on to the surface of the agar, and the plates are incubated. After 24 to 48 hours incubation, the specific component of the pool that satisfies the requirement of the mutant will be surrounded by a marked zone of growth, the size of which will depend on the rate of diffusion through the agar. The mutant is then labeled appropriately and its quantitative response to graded concentrations of its substrate is determined.

The minimal medium generally used in these experiments is that devised by Labrum and Bunting[18] for *Serratia marcescens*. For complete medium, this minimal medium is supplemented with yeast extract, casitone, and Bacto-peptone (2 gm of each per liter of minimal medium).

MINIMAL MEDIUM

K_2HPO_4 (anhydrous)	8.0 gm	Glycerol	20.0 ml
$(NH_4)_2HC_6H_5O_7$	5.0 gm	Distilled water	1.0 *l*
$MgSO_4 \cdot 7H_2O$	0.5 gm	Bacto-agar (optional)	15.0 gm
$FeNO_3 \cdot 9H_2O$	0.02 gm		

The application of these mutants to tests of sea water, including sampling methods, sterilization, and other procedures will be discussed in the experimental results section, along with the pertinent data.

Experimental Results.—By application of the techniques described in the preceding section, a number of nutritionally exacting mutant strains have been isolated. A list of the requirements of the mutants obtained to date follows:

Uracil	(3)	Histidine (Proline)	(2)
Tryptophane	(1)	Methionine (Cystine)	(1)
Threonine	(1)	Glycine	(1)
Isoleucine	(1)	Purine*	(20)—One culture lost in transfer
Biotin	(1)—Lost in transfer	Peptone^{+}	(3)
Adenine	(2)	Arginine	(1)

The number in parentheses following the biochemical indicates the number of separate mutants isolated with that requirement. The asterisk following purine indicates a nonspecific requirement for those mutants. All mutants respond to all of the purine bases, their ribosides and their ribotides. The dagger following peptone indicates that these three mutants respond to some component of peptone, probably complex, which is as yet unidentified.

At various times during the course of the isolation of the biochemical mutants, samples of sea water have been subjected to test analysis, using the mutants then available. Each group of samples will be considered separately in the following section, since different numbers of mutants were used.

The first group of water samples subjected to bioassay with mutants of *Serratia marinorubra* were collected for me by Dr. Galen E. Jones on a cruise in waters off Costa Rica.[19] The samples were taken in two ways. Surface samples were obtained by collecting with a clean plastic bucket, lowered over the side of the research vessel as soon as she was on station. Samples from various depths were taken in vertical casts using the Van Dorn sampler. All samples were immediately passed through Whatman No. 2 filter paper to remove large particulate material and then delivered into screw cap bottles and autoclaved. The samples were brought back to the laboratory for tests and were stored for varying times before testing. When the samples were returned to the laboratory, tests were set up as follows:

Sterile glycerol was added to the bottle to serve as energy source and two ml aliquots of each sample were delivered into sterile tubes. All tests were run with triplicate tubes. One set of tubes from each sample was held without inoculation as sterility controls, and one set was inoculated with each mutant. Another set was inoculated with the nutritionally independent parent culture as a viability control to make sure that the sea water could support growth of the bacteria and that no antibiotic substances were present. For each group of samples tested, a reversion control was run on each mutant to insure that reverse mutation to nutritional independence did not give false positive tests. Following a suitable period of incubation at ambient temperatures, the turbidity in the tubes was visually estimated. It is possible to read these tests in the Beckman DU spectrophotometer for quantitative estimation, but at this stage it seems more important to document the occurrence and distribution of nutrients than to attempt to quantitate them.

TABLE 1

Presence of Growth Factors in Sea-Water Samples as Indicated by Bacterial Mutant Growth and Correlations with Chlorophyll Determinations and Numbers of Free Bacteria in the Same Locations*

Date of Sample	SC	B	U	P	Depth in Meters	Chlorophyll, mg/m³†	Depth	Bacterial Count/ml‡
11/10/56	0	0	0	0	Surface	0.125	Surface	2
11/12/56	0	0	0	0	Surface	0.204	Surface	No count
11/15/56	0	++	0	0	Surface	0.577	Surface	34
11/16/56	0	0	0	0	Surface	0.380	Surface	546
11/21/56	0	±	0	0	Surface	0.308	Surface	...
,,	0	±	0	0	5	...	...	...
,,	0	0	0	0	10	0.310	8	...
,,	0	±	0	0	14	0.340	12	...
,,	0	0	0	0	18	0.342	16	187§
,,	0	±	±	0	22	0.335	20	4,200§
,,	0	0	0	0	27	0.458	30	383§
,,	0	0	0	0	50	...	...	...
,,	0	0	0	0	100	0.280	100	3,200
,,	0	0	0	0	200	0.092	200	...
12/1/56	0	0	0	0	Surface	0.329	Surface	75
,,	0	0	±	++	10	0.364	10	3
,,	0	0	±	0	50	0.491	50	1
,,	0	++	0	0	75	0.101	100	1
12/2/56	0	0	0	0	Surface	0.196	Surface	23
,,	0	++	0	0	5	No reading	5	6
,,	0	++	0	0	10	0.215	10	5
,,	0	++	+	0	25	0.261	25	2
,,	0	++	+	0	50	0.633	50	15
,,	0	+	0	0	75	No reading	75	5
,,	0	±	0	0	100	0.105	100	2
12/3/56	0	+	0	0	Surface	0.169	Surface	114
12/5/56	0	++	0	0	Surface	0.124	Surface	97
12/7/56	0	++	0	0	Surface	No reading	Surface	7
,,	0	++	0	0	25	0.905	25	14

* Each water sample was enriched with glycerol and equal volumes were delivered into four tubes. One was not inoculated, and served as a sterility control (SC). The other three, respectively, were inoculated with mutants requiring biotin (B), uracil (U), and purine (P). The tubes were scored after five days according to the following visual turbidity index: 0 = no turbidity, ± = faint turbidity, + = slight but definite turbidity, ++ = moderate and +++ = heavy turbidity.

§ These figures not considered valid because of type of sampler used.

† Data of R. W. Holmes.

‡ Data of Galen E. Jones.

When these samples were taken, only three mutants were available for the test. The results of these tests appear in Table 1.

These data indicate that soluble organic micronutrients are present in the sea and that they are sporadically distributed both horizontally and vertically. The results indicated that the technique has merit for this sort of work and encouraged us to continue isolating mutants for the assay. No attempts were made to test sea-water samples further until a sufficiently broad spectrum of nutritional mutant strains were available.

By November, 1958, we had isolated ten different mutants and had identified their requirements. These seemed to represent a sufficiently broad spectrum of assayable micronutrients to justify a rigid trial at sea. Arrangements were made for a technician to accompany a cruise to the Gulf of Tehuantepec under the auspices of the Scripps Tuna Oceanography Research Program of the U. S. Bureau of Commercial Fisheries. Samples were secured at the entrance to the Gulf, and at a number of stations in the Gulf. All of the samples taken on the Tehuantepec cruise were obtained by using the Van Dorn plastic sampler. A total of seven surface samples and nine 4-bottle vertical casts were taken. As soon as they were brought aboard, the samples were passed through Whatman No. 2 filter paper. About 150 ml of the filtrate from each sample were immediately delivered into screw-cap bottles, autoclaved, and stored at room temperature for future testing in the laboratory. Glycerol was added to the remaining portion of the sample, which was sterilized by one of two methods. Part of the experimental protocol was designed to test differences between autoclaving and sterile filtration, and the samples were either Seitz filtered and then added to sterile tubes, or added directly to tubes and then sterilized by autoclaving. These tubes were inoculated with the various mutant strains and incubated. They were scored at 4 and 8 days for turbidity. Some samples were incubated at ambient temperatures, others in a 29°C incubator, and still others in a water bath with circulating sea water at ambient temperatures.

All samples proved negative for organic materials by our test, and in fact, the nonexacting parental strain also failed to grow. Spot checks for antibiotic activity were also negative. It was suspected that possibly some inorganic constituent of the medium might be limiting in view of the failure of the nonexacting strain to grow, and so several tubes were supplemented with our basal medium. After this addition, the parental stock did grow and turbidity developed in those tubes. It was not until the samples were checked further in the laboratory that the limiting inorganic chemical was identified as the nitrogen source. As a result of a rather extensive set of experiments on the inorganic chemicals, the technique has been modified, and inorganic enrichment has been made a part of our protocol. The failure to get positive tests for organic micronutrients on this cruise, however, does not detract from the value of the method. The results confirmed the absolute nature of the response of the mutants to their specific substrates, and the application of the technique at sea for a period of five weeks permitted revision and improvement of the shipboard protocol.

The most extensive application of the bioassay method to sea-water samples has been in progress since December 15, 1958. On that date, there was initiated a series of twice-weekly samples from the Scripps Pier at La Jolla, California. The purpose of these samples is to examine changes over a period of time at one station, to give the technique a stringent test in terms of reproducibility, and to attempt to integrate the program with other types of work being done on the same samples.

As a result of the data from the Tehuantepec samples, we have included inorganic enrichment in all of these tests. The modified protocol for the pier samples is as follows:

Surface samples are taken by a bucket cast. The sample is filtered through Whatman No. 2 paper. Glycerol is added to the sample, and two ml aliquots are delivered into one set of tubes. Phosphate and nitrate enrichment is added to the remainder of the sample, and another set of tubes is prepared by sterile filtration. (This latter set is used in the tryptophane assay, since tryptophane breaks down on autoclaving.) The remainder of the enriched sample is delivered into tubes, and all but the tryptophane set are autoclaved. All tubes are inoculated with the mutant organisms, and one set is held as a sterility control. The nonexacting parental strain is always included as a viability control to detect antibiotic activity or inorganic chemical anomalies. In this series of tests, the biochemical requirements of the mutants are as follows:

Uracil
Isoleucine
Methionine
Histidine
Adenine
Peptone
Threonine
Tryptophane
Purine
Glycine

The results of these samples are best presented in graph form, since only two of them have occurred with regularity. A graph of the fluctuations in isoleucine and uracil appears in Figure 1. Glycine appeared in two samples, and all samples were completely negative for the other seven mutants.

General Discussion.—Although the data that we have obtained thus far in the program are highly provocative, it is felt that much more work is needed before we can attempt very definite conclusions in regard to the specific problems outlined in the introduction. The data do, however, constitute an adequate test of the bioassay technique, from the qualitative standpoint. The method is reliable, is reproducible, and can be controlled for reverse mutation that might give false results.

The discontinuity in the distribution of the biochemical compounds found in Table 1 both vertically and horizontally in the ocean is quite interesting. One would expect *a priori*, that these would exhibit a gradient effect in an aqueous environment, showing high concentration in a center, and diminishing concentrations toward the periphery. The observed discontinuity may be a reflection of localized physical phenomena such as internal waves, shearing effects of currents, and other factors of this nature which would impinge on a normal diffusion gradient. This aspect of the problem is amenable to test, and must be examined before definite conclusions are possible.

In the most recent phase of the work, where the bioassay has been applied to samples obtained from the Scripps Pier, there is an obvious variation in the concentration of biochemicals at a given point over a period of time. At this stage in the work, it is impossible to explain these fluctuations on the basis of the scant data available. The differences in concentration are real, but the underlying cause is unknown. It is interesting to speculate that the differences may result from a flow of water past the pier, or from biological uptake, but only with more data and refined techniques will definite interpretation be possible.

Summary.—A bioassay technique for organic micronutrients in sea water is described. The use of biochemically deficient mutant strains of a marine bacterium for this purpose is a novel approach, and the preliminary data indicate that the assays are valid.

The results of the application of the bioassay indicate that sea-water does, indeed, contain organic micronutrients. Of the ten substances assayed for, biotin, uracil, and isoleucine appeared most frequently. One occurrence of purine and two isolated occurrences of glycine were noted. More recently, tryptophan and threonine have each appeared in one sample.

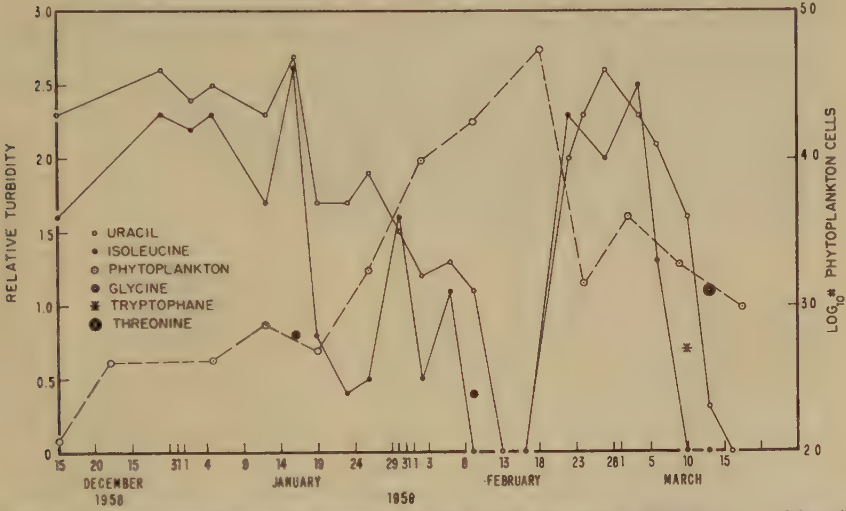

Fig. 1.—Occurrence of organic micronutrients in samples taken from Scripps Pier. Although ten different biochemicals were assayed for, only five were detected during this time period. The curve showing phytoplankton numbers is from data of Dr. B. M. Sweeney and Anne N. Dodson.

A series of weekly samples from a shore station have given much valuable information concerning the validity and reproducibility of the technique.

It is expected that extended application of the bioassay technique will elucidate some unexplained discontinuities in the distribution of marine organisms and may be of value in the description and identification of water masses and in tracing their movements.

The criticisms and suggestions made by Dr. Galen E. Jones on the experimental work have been particularly helpful, and the technical assistance of Miss Phyllis Bear and Mr. William A. Moller is gratefully acknowledged. The author would like to express his gratitude to Dr. Sweeney and Mrs. Dodson for making their data on phytoplankton populations available. He would also like to thank Dr. Carl L. Hubbs for his critical review on the manuscript.

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[1] Redfield, A. C., *Am. Scientist*, **46**, 205 (1958).

[2] Lucas, C. B., *Biol. Rev.*, **22**, 270 (1947).

[3] Provasoli, L., in Buzzati-Traverso, *A Symposium on Perspectives in Marine Biology* (University of California Press, 1958).

[4] Margalef, R., *Ibid.*

[5] Allen, E. J., *J. Mar. Biol. Assn. U. K.*, **10**, 417 (1914).

[6] Harvey, H. W., *Ibid.*, **23**, 499 (1939).

[7] Lewin, R. A., *J. Gen. Microbiol.*, **10**, 93 (1954).

[8] Sweeney, B. M., *Am. J. Bot.*, **41**, 821 (1954).

[9] Droop, M. R., *J. Mar. Biol. Assn. U. K.*, **37**, 323 (1958).

[10] Collier, A., *et al.*, *Science*, **111**, 151 (1950).

[11] Loomis, F., unpublished, 1953.

[12] Wilson, D. P., in Buzzati-Traverso, *A Symposium on Perspectives in Marine Biology* (University of California Press, 1958).

[13] Lewin, R. A., *Can. J. Bot.*, **33**, 5 (1955).

[14] Provasoli, L., and I. J. Pintner, *Proc. Soc. Protozoologists*, **4**, 10 (1953).

[15] Johnston, R., *J. Mar. Biol. Assn. U. K.*, **34**, 185 (1955).

[16] Zobell, C. E., and H. Upham, *Bull. Scripps Inst. Oc.*, **5**, 239 (1944).

[17] Lederberg, J., and E. Lederberg, J., *Bacteriol.*, **63**, 399 (1952).

[18] Labrum, E. L., and M. I. Bunting, *J. Bacteriol.*, **65**, 394 (1953).

[19] Belser, W. L., *Spec. Sci. Repts.-Fisheries #279*, 55 (1958).

Effects of Some Aspects of Environment on the Distribution of Juvenile Herring in Barkley Sound[1, 2]

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ABSTRACT

During the early juvenile stage, the herring in Barkley Sound move from the spawning grounds, mainly on the northwest side of the sound, to rearing grounds mainly on the southeast side. From a study of the distribution abundance and environment of the juveniles, it would appear that the herring were neither carried across the sound by prevailing currents nor were they simply following their food supply. The fish appear to have dispersed and gradually collected in the sheltered bays, inlets and channels, which are more numerous on the southeast side. Juvenile habitats generally had shallow thermoclines, medium salinities and below average zooplankton concentrations but these factors did not appear to affect the distribution of the juveniles directly.

INTRODUCTION

GENERAL BACKGROUND

HERRING spawn in Barkley Sound (Fig. 1) on the west coast of Vancouver Island from late January to early April. The larvae hatch in about two weeks and are gradually dispersed from the spawning grounds. During the larval period the abundance per unit volume of water decreases with the distance from a spawning ground (Stevenson, MS, 1955). In six to eight weeks the larvae metamorphose into juveniles. A month or so later the juveniles begin to form relatively large schools. In a survey of the juvenile herring in Barkley Sound in 1951 through 1954 (Hourston, 1958a), schools of juveniles were found mainly in inlets and bays and around islands (Fig. 3). On the other hand, spawning during these years took place mainly along the Macoah Passage shore (Fig. 4—Stevenson *et al.*, 1951; Stevenson *et al.*, 1952; Stevenson and Outram, 1953; Taylor and Outram, 1954). Studies of various aspects of the environment were carried out in conjunction with the surveys of juvenile abundance in an effort to determine the cause of this change in distribution.

JUVENILE HERRING BEHAVIOUR

Juvenile herring schools were found just below the surface (2 to 20 feet) at dawn and dusk, when they appeared to be actively feeding. During the day they were observed at slightly greater depths (10 to 50 feet) when they showed little signs of feeding activity. Due to practical considerations, no attempts were made at comprehensive surveys during the hours of darkness. Occasionally schools were observed near the surface at night but these appeared to be relatively inactive and it is considered unlikely that feeding is extensive at this time. Since juvenile herring are strong swimmers and thus are relatively independent of the direct

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influences of current it seems likely that they seek out their food under optimum feeding conditions available at dawn and dusk. Many, if not most pelagic organisms, make daily journeys from deeper water to the surface at the approach of darkness and begin to return to deeper water at or before the break of dawn (Sverdrup *et al.*, 1942, p. 836). Thus the periods about dawn and dusk would be the only times at which the zooplankters upon which the juvenile herring feed would be both relatively concentrated and visible to their predators.

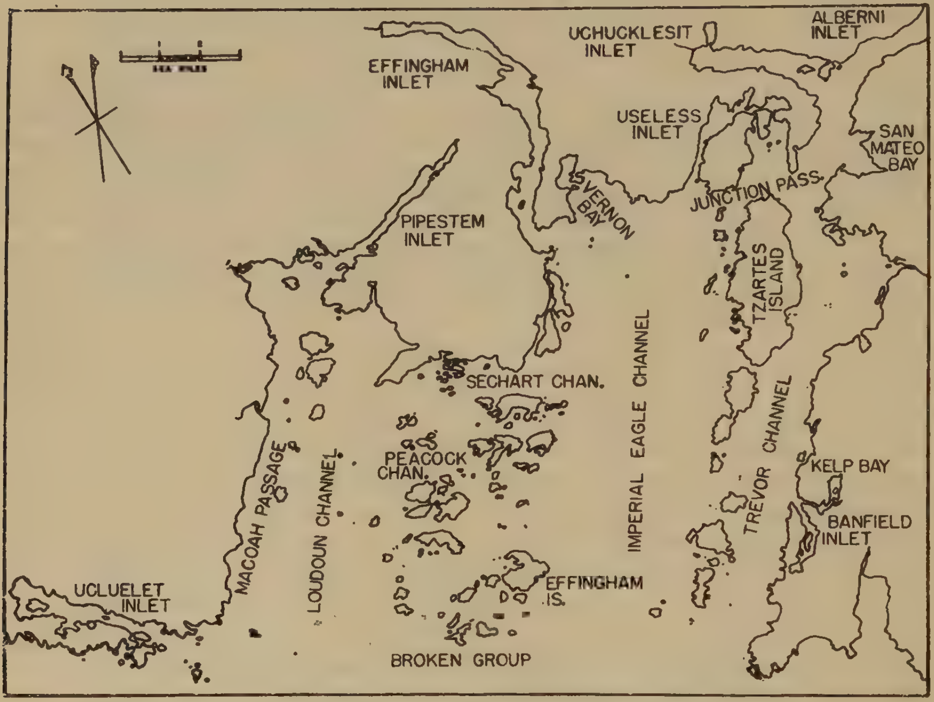
UCHUCKLESIT INLET
ALBERNI INLET
EFFINGHAM INLET
USELESS INLET
SAN MATEO BAY
JUNCTION PASS.
VERNON BAY
PIPESTEM INLET
TZARTES ISLAND
IMPERIAL EAGLE CHANNEL
SECHART CHAN.
TREVOR CHANNEL
PEACOCK CHAN.
KELP BAY
MACOAH PASSAGE
LOUDOUN CHANNEL
BANFIELD INLET
UCLUELET INLET
EFFINGHAM IS.
BROKEN GROUP

FIG. 1. Map of Barkley Sound showing localities mentioned in the text.

DESCRIPTION OF BARKLEY SOUND

Barkley Sound is the most southerly major indentation on the southwest side of Vancouver Island. It runs in a southwest-northeast direction, between 48° 47′ and 49° 02′ North Latitude and between 124° 35′ and 125° 35′ West Longitude. Physiographically, Barkley Sound consists of the mouths of three inlets of varying size—Alberni, Effingham and Pipestem. During the Ice Age channels were gouged out by moving glaciers in all these inlets but particularly Alberni Inlet. Land masses separating the channels have been broken through by ice erosion and other elements sometime in their geological history. The island groups are remnants of these land barriers. Two chains of islands break it into three major channels—Trevor Channel along the southeast side between the Tzartus Island chain and the mainland of Vancouver Island, Imperial Eagle Channel between the Tzartus

(712)

Island chain and the Broken Group in the middle of the sound and Loudoun Channel between the Broken Group and the northwest shore. Sill depths at the mouths of these channels are 25, 61 and 42 fathoms, respectively (Fig. 2). The sound is surrounded on three sides by mountains, mainly 2,000 to 4,000 feet above sea level. The major source of runoff is the Somass River emptying into Alberni Inlet at the head of Trevor Channel. A second appreciable source is that from the Toquart River and nearby streams, and the Maggie River in the northwest corner of the sound, both running out through Macoah Passage.

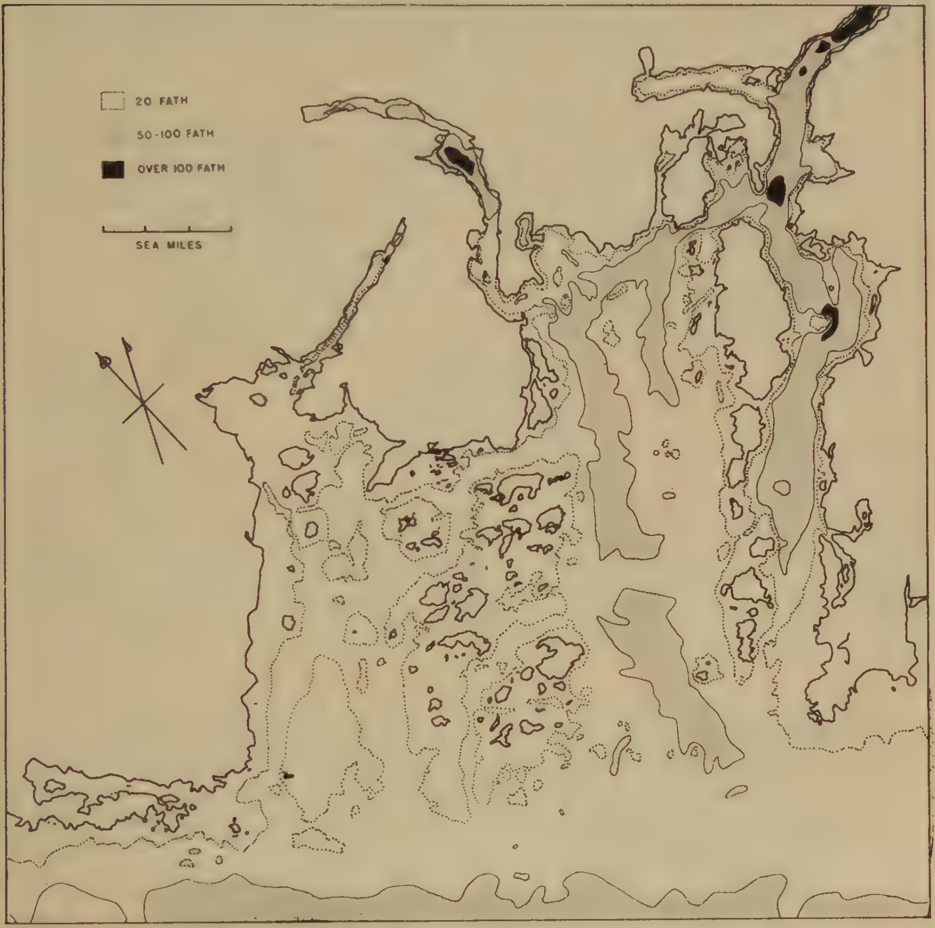

FIG. 2. Map of Barkley Sound showing major depth contours.

RESULTS

Early in the juvenile stage, the herring in Barkley Sound move from the spawning grounds, mainly on the northwest side of the sound, to rearing grounds

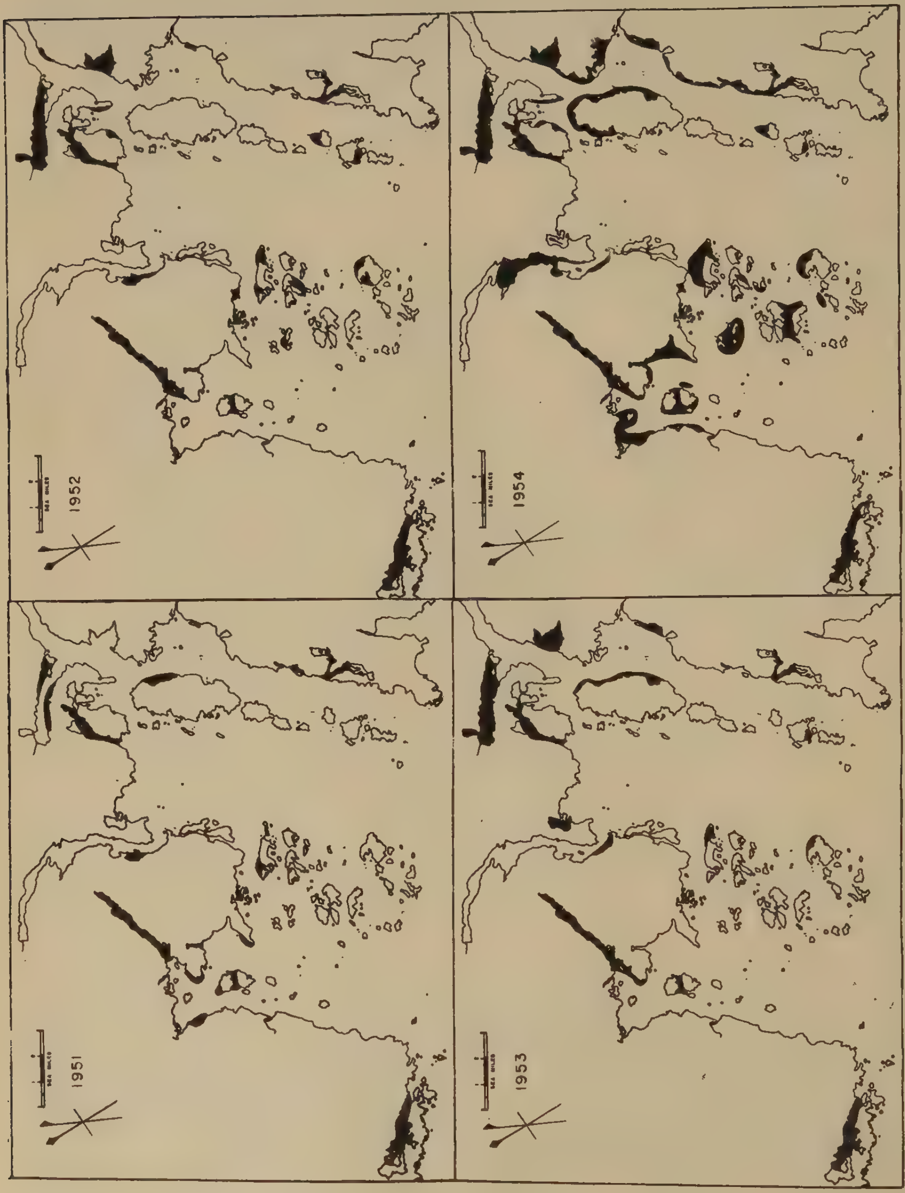
1952
1954
1951
1953
SEA MILES

FIG. 3. Localities in Barkley sound (shown in black) where juvenile herring schools were found, 1951–1954.

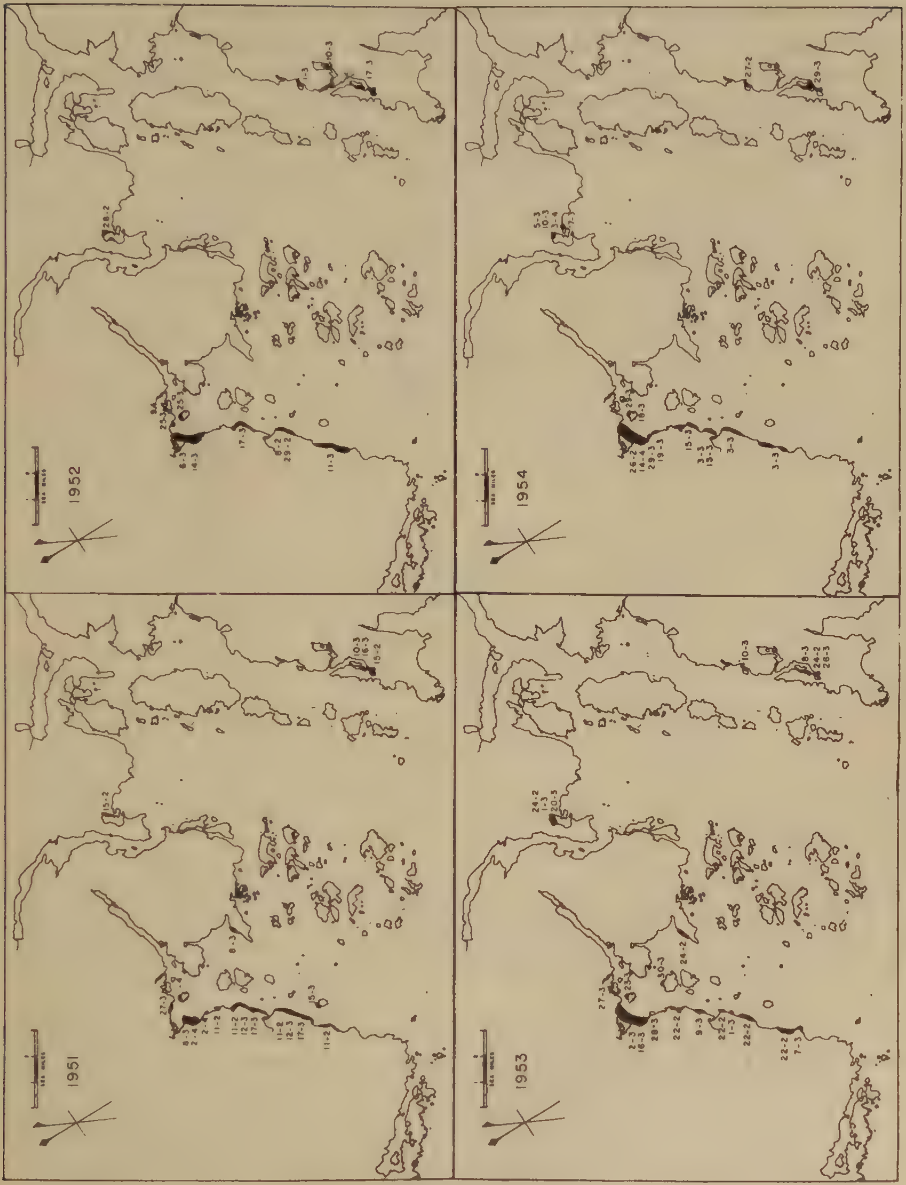
1952
10-3
17-3
28-2
25-3
6-3
14-3
17-3
8-2
29-2
11-3
1954
27-2
29-3
5-3
10-3
3-4
18-3
26-2
14-4
29-3
19-3
15-3
3-3
13-3
3-3
3-3
1951
10-3
16-3
15-2
15-2
8-3
27-3
8-3
2-4
2-3
11-2
11-2
12-3
17-3
11-2
12-3
17-3
15-3
11-2
1953
10-3
8-3
24-2
26-3
24-2
1-3
20-3
24-2
30-3
27-3
2-3
16-3
28-3
22-2
9-3
22-2
1-3
22-2
22-2
7-3

FIG. 4. Locations and dates of herring spawnings in Barkley Sound, 1951–54.

mainly on the southeast side. This change in distribution could be merely the end result of a passive transport of the young herring by the prevailing currents from the spawning grounds across the sound to the rearing grounds. This same mechanism could work indirectly by transporting the food supply (small zooplankton) of the juvenile herring with the fish themselves following. On the other hand, these fish could be actively seeking a more suitable environment, even if they merely disperse from the spawning grounds and then tend to collect in the more favourable environments. In the former alternative the movement may be considered as the cause of the change in distribution; in the latter it would be merely a means of achieving a change in distribution. These two alternatives will now be examined in the light of the data available on the environment of the juvenile herring.

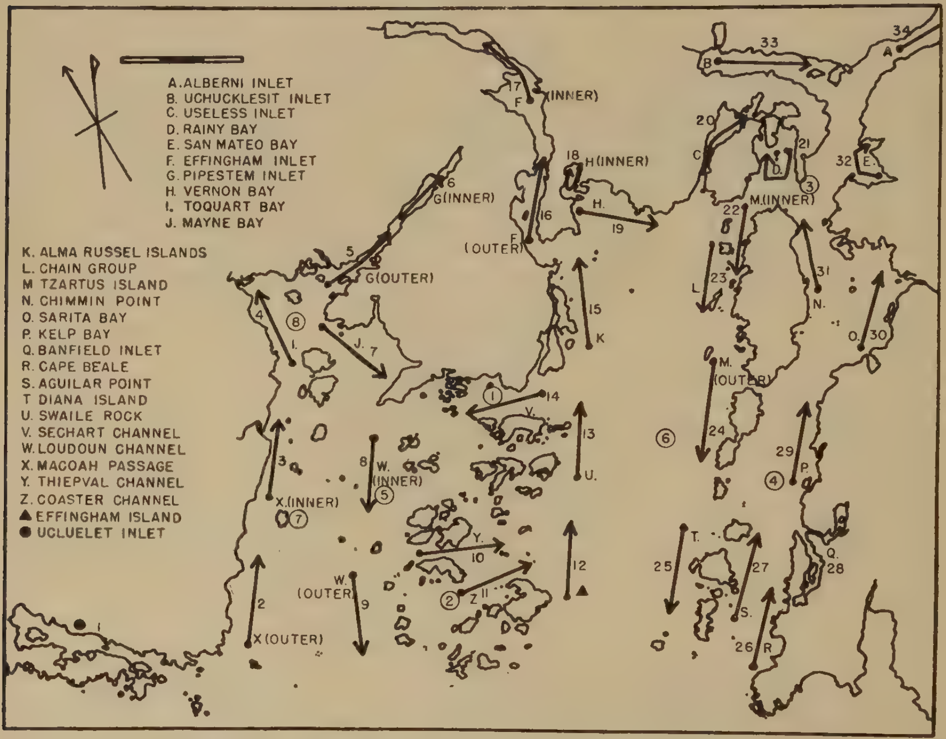
A. ALBERNI INLET
B. UCHUCKLESIT INLET
C. USELESS INLET
D. RAINY BAY
E. SAN MATEO BAY
F. EFFINGHAM INLET
G. PIPESTEM INLET
H. VERNON BAY
I. TOQUART BAY
J. MAYNE BAY
K. ALMA RUSSEL ISLANDS
L. CHAIN GROUP
M. TZARTUS ISLAND
N. CHIMMIN POINT
O. SARITA BAY
P. KELP BAY
Q. BANFIELD INLET
R. CAPE BEALE
S. AGUILAR POINT
T. DIANA ISLAND
U. SWAILE ROCK
V. SECHART CHANNEL
W. LOUDOUN CHANNEL
X. MACOAH PASSAGE
Y. THIEPVAL CHANNEL
Z. COASTER CHANNEL
▲ EFFINGHAM ISLAND
● UCLUELET INLET
F (INNER)
H (INNER)
G (INNER)
F (OUTER)
G (OUTER)
M (INNER)
M (OUTER)
W. (INNER)
X. (INNER)
W. (OUTER)
X (OUTER)

Fig. 5. Map of Barkley Sound showing stations for synoptic surveys and surface current measurements in 1954. Bathythermograph casts, surface temperatures, salinity determinations and meteorological observations were taken at dots; plankton hauls were taken along arrows. Numbers circled indicate stations for surface current measurements.

The Case of Passive Movement as the Direct Cause of the Change in Distribution

If the movement is passive, the water circulation in the sound must be such that it would tend to carry the fish and their microenvironment across the sound from the spawning grounds on the northwest side to the rearing grounds on the southeast side. Since juvenile herring are active swimmers and well able to hold their position independent of currents of the strength found in this region, it seems probable that any passive movement would result from the fish maintaining themselves in a moving microenvironment.

The upper limits of juvenile schools observed at dawn and dusk during the population surveys were usually within 10 feet of the surface. While schools were seldom observed during the day in these surveys, observations on the early juvenile stage in 1951 indicated that when the change in distribution of the young herring begins, many schools occupy comparable depths during the day as well as at dawn and dusk. Since the daylight period is appreciably longer than that of darkness in this region at this time of year, it would appear that the major effects of water circulation on juvenile distribution would take place in the surface region.

The thermocline in Barkley Sound was shallow where observed during this study, usually at a depth of 20 feet or less. Consequently, measurements of surface current had to be confined to the upper 15 feet or so. To this end a 14-foot drift pole of 2 × 4 inch timber, weighted at one end, and with a light mounted on the other end, was used to measure surface current. Direction of drift was obtained by sighting a compass on the after deck of an anchored vessel onto the pole. Distance drifted was measured by a small line ($\frac{1}{16}$ inch diameter) with corks tied on at intervals of about 50.7 feet, so that two corks in one minute represented a current of one knot.

Drift pole observations were made every half hour for a 25-hour period at eight stations in Barkley Sound during July and August, 1954 (Fig. 5). Stations 1, 2 and 5 were repeated under different wind conditions.

From frequency distributions of direction of flow at 20-degree intervals, it appeared that the currents at four of the eight stations showed a more or less simple reversal along an axis of about 100°–280° (i.e., across the sound). The currents at these stations were, therefore, resolved into their components along this axis and plotted, together with tidal height and wind direction and force (Fig. 6). The other four stations showed a sizeable in-and-out component along a 40°–220° axis, and both this component and the cross-sound component were plotted for these stations (Fig. 7). The area enclosed by each curve above and below the base line (determined by planimeter) gives the position and negative components respectively of the vectors plotted. These components are shown for all stations in Fig. 8.

At five of the eight stations the flow was predominantly cross-sound, but except for Stations 5 and 11 (in Loudoun Channel off Peacock Channel) the flow was greater towards the northwest than towards the southeast side. (Easterly flow predominated very slightly at one of two Sechart Channel stations.) Westerly winds predominated during the occupation of five stations and southeasterly during two, whereas at four the wind did not blow consistently from either direction. Thus, wind could not have been the major factor in the movement of the surface water. An increase in the extent of southeast winds in Loudoun Channel (Station 11 as compared with Station 5) did not appear to have appreciably affected the direction of flow, and an increase in the extent of westerly winds in Sechart Channel (Station 1 as compared with Station 9) and Coaster Channel (Station 2 as compared with Station 10) occurred at a period of increased rather than decreased

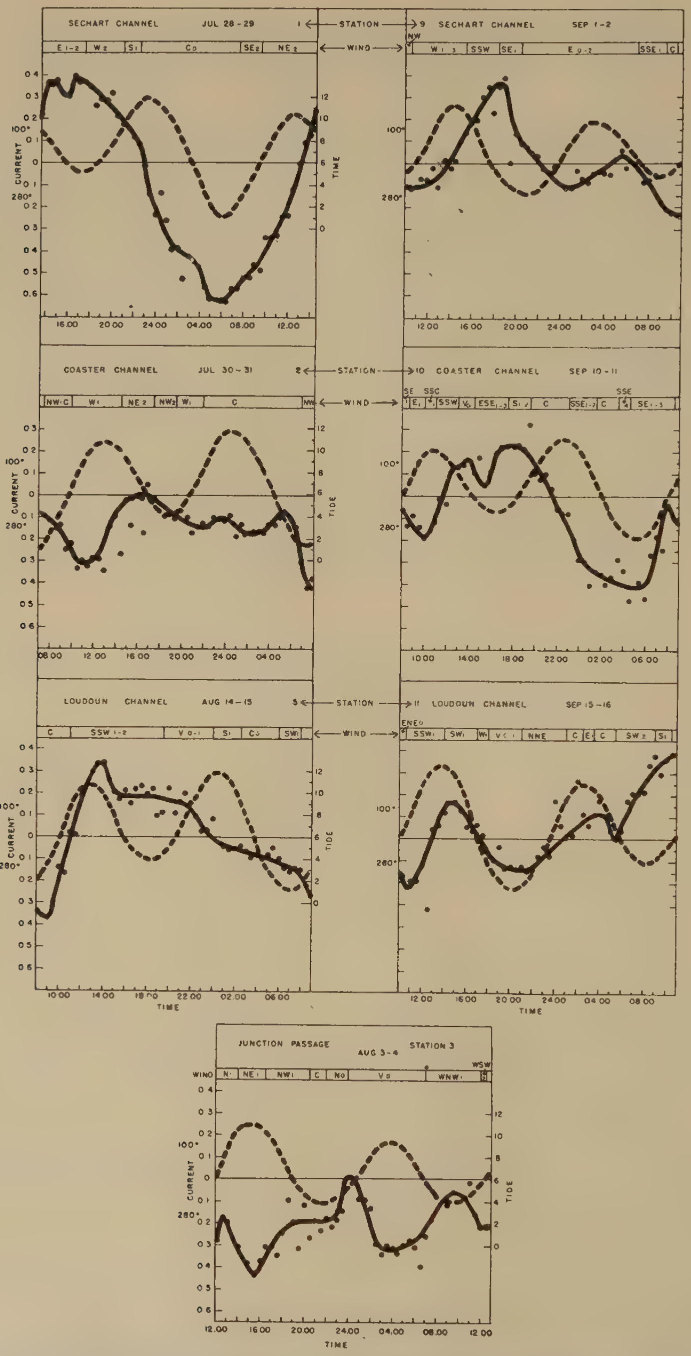

Fig. 6. Cross-sound surface currents in knots at the four localities (three repeated) in Barkley Sound in which the major flow appeared to be in the cross-sound direction only. Tidal height and wind conditions are also given.

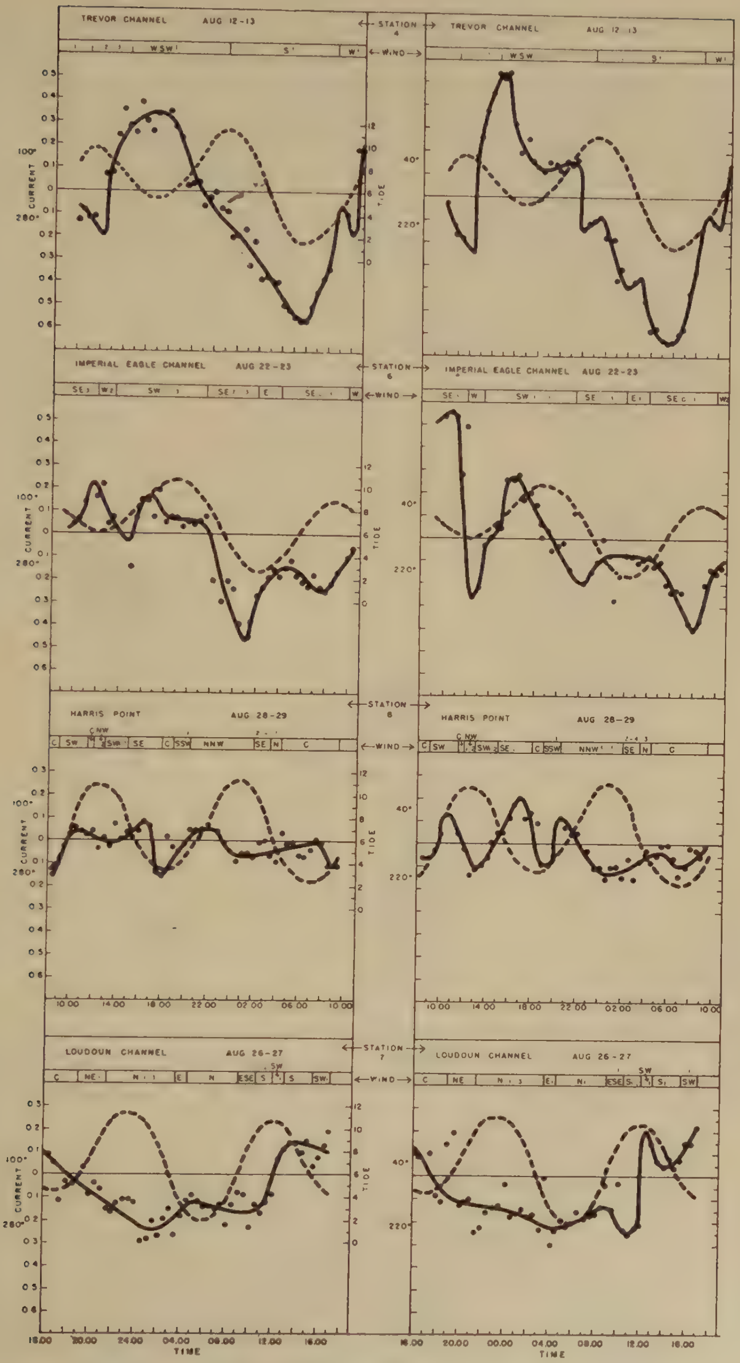

FIG. 7. Surface currents in knots across Barkley Sound (left) and in and out of the sound (right) at the 4 stations where flow in the latter direction was significant. Tidal height and wind conditions are also given.

flow to the west. Thus, except for small variations in the current curves, wind does not seem to have had much effect on the surface circulation. However, the winds involved were generally small (less than Beaufort Force 3) and would not have blown with sufficient strength for a long enough time to have any major effect.

The single daily current cycle occurring with a twice daily tidal change, which was described in this region by Doe (1952), was evident at Station 1, and it may have been observed at Stations 4, 5 and 10. Doe attributed this to a differential rate in tidal rise and fall on either side of the sound, or to a difference in the width of the tidal front. He considered runoff to be the dominant factor in the surface circulation in April. Since runoff in this region reaches its maximum in June, the effect of this factor would probably be equally great from mid-July to mid-September as in April, and should thus be just as dominant in summer as in April. This is borne out by the fact that surface flow throughout the sound seems to be generally away from the principal freshwater source, the Somass River in Alberni Inlet. Indeed, surface salinity west of the Broken Group (see below) indicates this water probably came through the Broken Group from Imperial Eagle Channel, rather than from the region of Toquart Bay and Loudoun Channel.

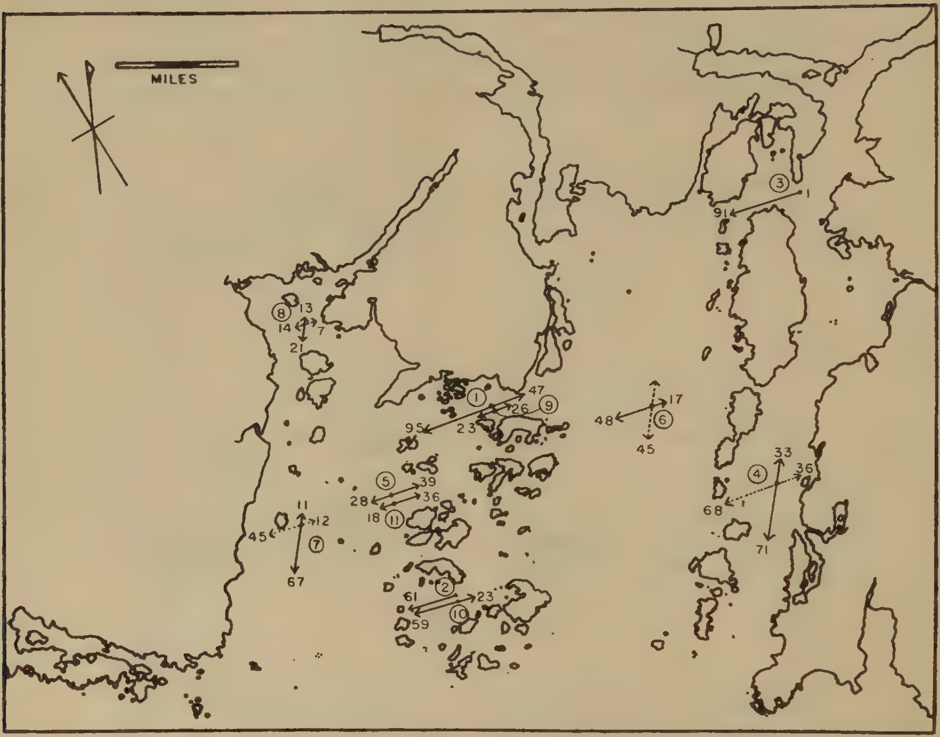

FIG. 8. Total cross-sound surface currents (knots) for semi-hourly observations over a 25-hour tidal cycle at eight stations in Barkley Sound during the summer of 1954. In-and-out flow is also shown where appreciable; solid lines indicate the direction in which flow is stronger; dotted lines, flow of less intensity.

(720)

Since the surface water appears to flow principally westerly, a counter-flow at some other depths would be expected from considerations of density flow. As the surface of fresh water with entrained sea water flows westward across the sound and seaward, a compensating flow of sea water must return at greater depths. In April, 1950, Doe (1952) observed a counter-flow close to Station 5 at a depth of 3 fathoms, and a northeasterly flow at depths of 3, 4 and 10 fathoms near Station 9. No current measurements at these depths were obtained in 1956 but it seems likely that the overall circulation system was similar to that observed by Doe. One check on this assumption is available from the 1956 data. Such a system of circula-

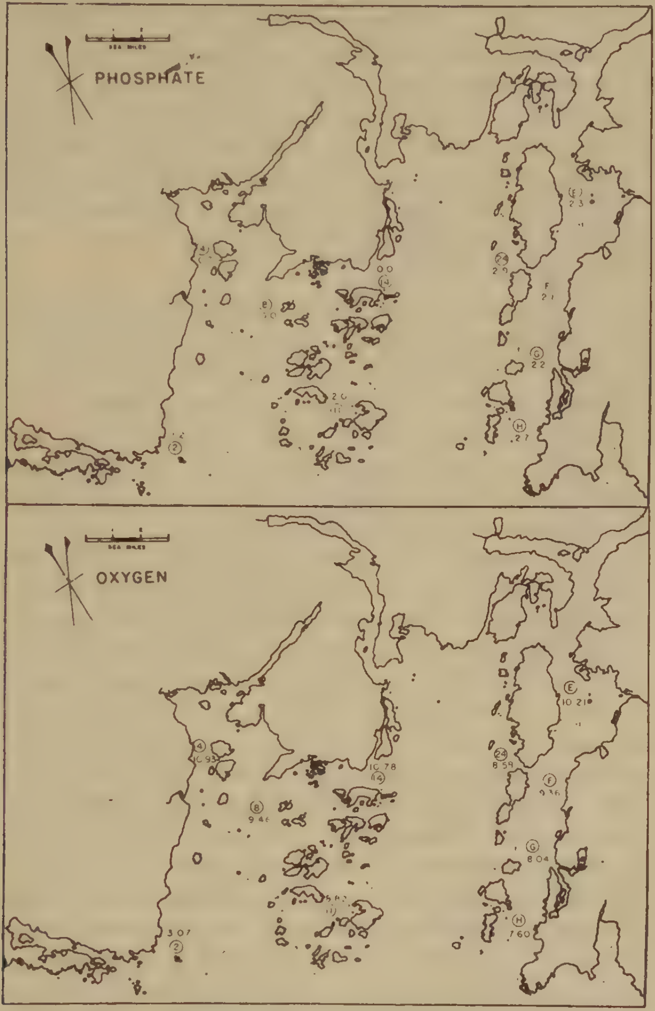

FIG. 9. Surface phosphate concentrations in microgram atoms per litre and oxygen concentrations in milligrams per litre at 10 stations in Barkley Sound on September 8, 1954.

tion would be expected to produce upwelling along the southeast side of the sound. Upwelling usually results in a higher-than-average nutrient content where it occurs. Observations of the relative abundance of surface phosphate and oxygen were made on September 9, 1954, at synoptic Stations 2, 4, 8, 11, 14 and 24 (Fig. 5), at Tully's (1949) Stations H, G, and E, which correspond fairly closely with Stations 27, 29 and 31, and at Tully's Station F, out in mid-channel from Station 30. Stations on the southeast side of the sound (24, E, F, G and H) and Station 11 showed a high phosphate (2.1–2.9 μg-atoms/l.) and low oxygen (7.60–10.21 mg/l.) content, while those on the northwest side showed the opposite trend (Fig. 9). The oxygen determination for Station 2 was extremely low, and was considered to be in error; the phosphate content was medium. Thus there would appear to be upwelling and greater productivity on the southeast side, supporting the circulation system proposed above.

Assuming the circulation pattern was as outlined, how would it direct the movements of the young herring? It has been noted above that the juveniles tend to frequent the surface regions at dawn and dusk and probably during the night, but that during the day they are usually found in deeper waters. If they were passively moving with the current, or following food organisms which were passively drifting, they would be moving towards the northwest side of the sound while in the surface waters at night and towards the southeast side while at greater depths during the day. Since the period of daylight is about twice as long as that of darkness during a 24-hour period in Barkley Sound at this time of year, and since currents at the surface are about twice the strength of those flowing in more or less the opposite direction 3 to 5 fathoms down, the net movement of these organisms during a 24-hour period should be approximately nil. This hypothesis assumes, however, that a large majority of the fish are in the surface water layer flowing toward the northwest side during darkness, and are below this layer in daylight. But the surface layer is so shallow that it is quite conceivable that the average fish (and food organism) does not spend all or even a very large proportion of the night in this layer. On the other hand, these organisms are not likely to leave the deeper waters and enter the surface layer to any extent during the day, as prevailing light conditions would make them extremely vulnerable to predation. Although schools of very young juveniles were observed near the surface during the day this phenomenon disappeared long before the change in distribution was accomplished. The net result of the organisms passively moving with the water masses they inhabit could thus be a gradual displacement of these organisms towards the southeast side of the sound and a general distribution similar to that shown by the juvenile herring.

Under these circumstances the distribution of the herring and their zooplankton food would be similar. The relative abundance of these two groups or organisms was therefore compared. Weekly surveys of the amount of smaller zooplankton present during the summer at 34 stations throughout Barkley Sound (Fig. 5) were carried out as part of the 1954 program. A Hardy small plankton sampler was towed at a depth of about 15 feet for a distance of approximately two miles through the water, resulting in the straining of about one cubic meter of water (Glover, 1953). A high speed plankton sampler was employed in order to permit maximum sampling in a short period (2 days) and thus make the hauls as comparable as possible on a time basis. Hauls were taken at a standard depth in order to permit comparisons between stations. No. 4 Dufour bolting silk was used (62 meshes to the inch) in the sampler's net in order to allow the smaller plankton forms, which are not fed upon by the herring, to escape. Also, because of its small orifice, this sampler excludes many coelenterates, ctenophores and other large planktonic organisms which would not play any part in the diet of young herring. Volumetric analysis was carried out on board ship on the sample as a whole using Frolander's (1954) plankton volume displacement indicator. Abundance of these zooplankters (Fig. 10) was below average near the main rearing grounds (on the southeast side) and highest in the western corner near the main spawning grounds. Thus, if the zooplankton were concentrated by the water currents on the southeast side of the sound their numbers must have been reduced by a higher rate of predation from a level above that on the northwest side to a level below that on the northwest side. A reduction in zooplankton abundance of this order is quite possible considering the abundance and concentration of the feeding juveniles. On the other hand, if the juveniles were merely following their food supply to the southeast side of the sound, why did they not disperse again towards the northwest side when food became relatively more abundant there? Also, there is a counter-current up

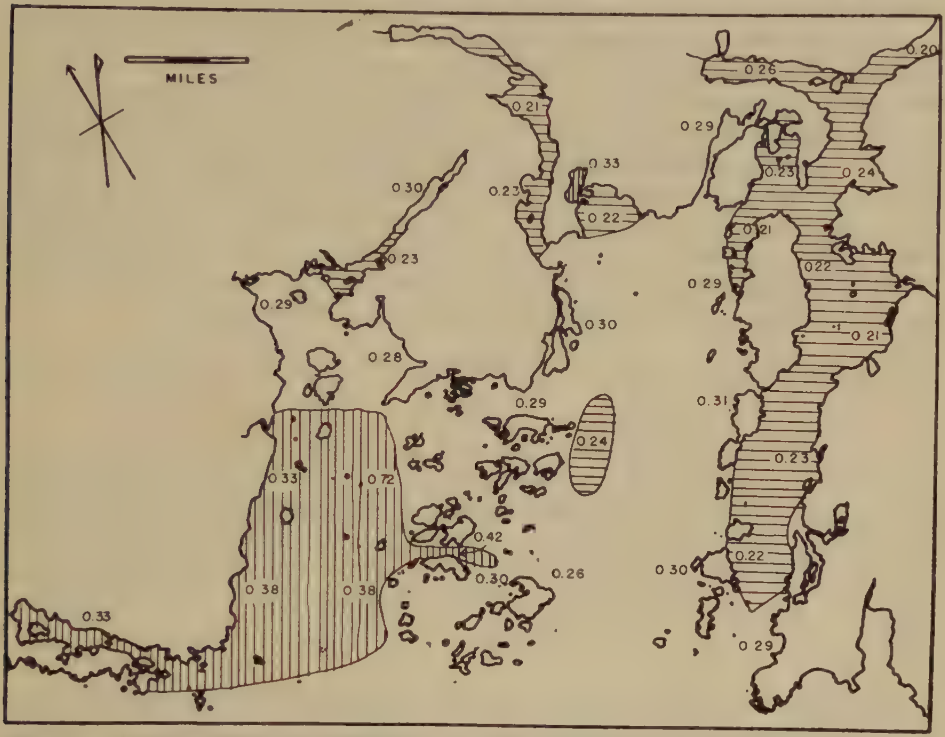

FIG. 10. Average volume of zooplankton, in cubic centimeters per cubic meter, at each of the 34 synoptic stations in Barkley Sound during 1954.

Alberni Inlet at mid-depths (Tully, 1949) but no major concentrations of either juveniles or zooplankton were located during the occasional general surveys made in this inlet. If the fish and/or their food supply were passively carried across the sound by the sub-surface counter current, it would be expected that once they reach the southeast side, they would be carried up Alberni Inlet by the counter current in this region.

Thus it is possible that the juvenile herring and/or their zooplankton food supply spend a sufficiently large portion of their time at depths below 3 to 5 fathoms to be carried passively by currents at these depths towards rearing grounds on the southeast side of the sound. However, neither the juveniles nor the zooplankton appear to be transported up Alberni Inlet in appreciable numbers as would be anticipated if they were passively drifting at these depths. Instead, the young herring on the southeast side tend to move seaward as the summer progresses rather than up Alberni Inlet (Hourston, 1958). Thus, the case for passive movement as the direct cause of the change in distribution of the young herring does not appear to provide a reasonably satisfactory explanation for this change.

THE CASE FOR MIGRATION BY DISPERSING AND THEN STAYING WHERE CONDITIONS ARE FAVOURABLE

If the juvenile herring actively seek more favourable environmental conditions than those near the spawning grounds, or if they disperse from the spawning grounds and collect in the localities where the environment is most favourable, then one or more environmental conditions on the rearing grounds must differ from those elsewhere. Several aspects of the environment were examined for such differences.

1. SALINITY

Recent studies on adult herring in British Columbia have indicated a possible relationship between the presence of herring and the salinity of their environment (Hourston, 1953b). Preliminary investigations of a possible relationship between the distribution of juveniles and salinity were therefore carried out in 1952 and 1953. This study was aimed at comparing the salinities in localities where herring were absent, present, and abundant.

Statistical comparisons of the abundance of juvenile herring and the salinities at each of a series of depths were made between the above three categories using the “*t*” test (Snedecor, 1946) with the following results:

	1952		1953	
Depth	Abundant vs. Absent	Present vs. Absent	Abundant vs. Absent	Present vs. Absent
feet				
0	$P \approx 0.70$	$P > 0.90$	$P \approx 0.50$	$P \approx 0.30$
10	$P \approx 0.40$	$P \approx 0.35$	...	...
20	$P > 0.90$	$P = \infty$	$P \approx 0.40$	$P \approx 0.80$
40	$P \approx 0.85$	$P > 0.90$	$P \approx 0.01$	$P \approx 0.12$
60	...	...	$P < 0.01$	$P \approx 0.02$

(724)

Very significant differences in salinity at a depth of 40 feet were found between the samples taken where juveniles were abundant and those taken where juveniles were absent in 1953. The juveniles appeared to prefer the less saline water (31.2–31.5 parts per thousand). The comparison of present vs. absent was also significant at the 60-foot depth. However, no such differences were noted in the 1952 samples, so it is doubtful if these differences have any biological significance. This is especially so since the juveniles tend to be found in the upper 50 feet of water.

Observations were also classified by locality. Each locality surveyed was designated as a good or poor juvenile rearing ground, on the basis of observed juvenile abundance throughout the entire summer. Salinity samples from both types of grounds were then compared as above for significant differences, with the following results:

Depth	1952	1953
feet		
0	$P \approx 0.15$	$P \approx 0.40$
10	$P \approx 0.45$	...
20	$P \approx 0.45$	$P \approx 0.70$
40	$P \approx 0.70$	$P \approx 0.40$
60	...	$P \approx 0.20$

No significant differences were found between categories in this grouping, thus casting further doubts on the differences found in the first grouping, to which it would be expected to show some relationship. Juveniles were not only present but abundant in a wide range of surface salinities, from the smallest observed (14.13 in Uchucklesit Inlet, 1952), to the largest (31.13 in Ucluelet Inlet, 1952). This situation obtained at all depths.

However, localities where juveniles were consistently abundant tended to show a wider range in salinity with depth (e.g. 14.13 to 31.97 in Uchucklesit Inlet). Salinity ranges between the surface and 20 feet for the 1952 data (most samples were taken in less than 40 feet of water) and between the surface and 60 feet for the 1953 data were therefore similarly tested, with the following results:

Year	Abundant vs Absent	Present vs Absent	Rearing grounds Good vs Poor
1952	$P > 0.5$	$P > 0.6$	$P > 0.7$
1953	$P > 0.05$	$P > 0.1$	$P > 0.05$

Thus the abundance of juveniles was not significantly related to salinity gradients either.

In 1954, emphasis was shifted to determining the general salinity picture for the sound in relation to the presence of juveniles.

Surface salinity samples were taken at each station during the synoptic surveys (Fig. 5). Samples were taken from a bucket of sea water drawn up from about two feet below the surface. Samples taken during the first survey were analyzed by hydrometer, but since the set was not complete and the results seemed remarkably low, samples from the remainder of the surveys were analyzed by titration. Averages were determined for the last eight surveys (Fig. 11).

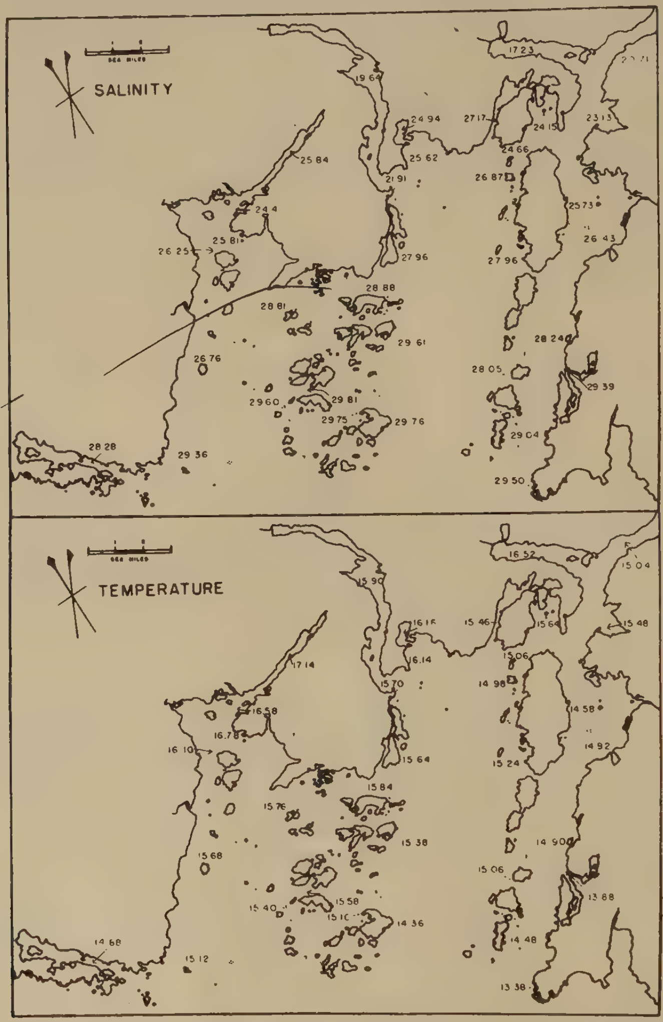
SALINITY
SEA MILES
17 23
19 64
24 94
27 17
24 15
23 13
25 84
25 62
24 66
21 91
26 87
24 4
25 73
25 81
26 25
27 96
26 43
27 96
28 88
28 81
29 61
28 24
26 76
28 05
29 39
29 60
29 81
29 75
29 76
29 04
28 28
29 36
29 50
TEMPERATURE
SEA MILES
16 52
15 04
15 90
16 16
15 46
15 64
15 48
17 14
16.14
15 06
15 70
14 98
16 58
14 58
16.78
16 10
15 64
15 24
14 92
15 84
15 76
15 38
14 90
15 68
15 06
13 88
15 40
15 58
15 10
14 36
14 68
15 12
14 48
13 38

FIG. 11. Average surface salinities and temperatures at 34 stations in Barkley Sound during 1954.

Relatively high salinities occurred at the mouth of the sound and around the Broken Group. Thus the major outflow and runoff occurred down either side of the sound (Loudoun Channel on the west and Imperial Eagle Channel and Trevor Channel on the east).

In localities where juveniles were consistently abundant, average salinities varied from 17.23‰ (Uchucklesit Inlet) to 29.39‰ (Banfield Inlet), thus indicating a wide tolerance range. However, the salinities in most of these regions run from 23 to 27‰. Buchmann *et al.* (1953) found that young Atlantic herring (*Clupea harengus*) in the North Sea move after metamorphosis from the highly saline offshore waters to the more brackish waters off estuaries. Fujita and Kokubo (1927) found that Japanese herring fry survive best in $4/5$ sea salinity, followed in order by $3/5$, $2/5$, $1/5$, $1/10$ and $5/5$; in the latter they lasted only a few hours. Surface salinities in the ocean off Barkley Sound are about 31‰ (Waldichuk, unpublished data) and thus, if the same situation applies in Barkley Sound, the young herring would be expected to survive best in salinities of about 25‰. This suggestion fits very well the observed abundance of juvenile herring in Barkley Sound and the average salinities where juveniles were captured during 1954, except for Uchucklesit Inlet, which contained a good population of juvenile herring, but had a relatively low salinity. However, the juvenile schools within the inlet tended to concentrate nearer to the mouth (and thus farther away from the fresh water inflow) than the synoptic station and were thus probably in more saline water than indicated.

2. TEMPERATURE

Temperature data were recorded in conjunction with water sampling for salinity data. Reversing thermometers were employed in 1952 and 1953, and the 1953 temperatures were checked with simultaneous bathythermograph casts. All 1954 data were taken by bathythermograph, with readings corrected to surface temperatures taken from bucket samples. Analysis was similar to that employed on the salinity data. Comparisons of temperatures where herring were abundant, present and absent are given below:

	1952		1953	
Depth	Abundant vs. Absent	Present vs. Absent	Abundant vs. Absent	Present vs. Absent
feet				
0	$P < 0.001$	$P < 0.01$	$P \approx 0.25$	$P \approx 0.20$
10	$P < 0.02$	$P \approx 0.03$	...	...
20	$P \approx 0.10$	$P \approx 0.10$	$P \approx 0.40$	$P \approx 0.82$
40	$P \approx 0.50$	$P \approx 0.50$	$P \approx 0.025$	$P \approx 0.40$
60	...	...	$P < 0.01$	$P \approx 0.60$

Very significant differences were found in surface temperatures in 1952 for both classifications. These differences were also significant at a depth of 10 feet. The juveniles seemed to prefer colder surface water. However, the 1953 data failed to support these indications. In 1953 a significant difference was found at a depth of 60 feet between localities where juveniles were abundant and where they were absent, the juveniles apparently preferring the warmer water. This difference was also significant at 40 feet. The 1952 data failed to substantiate this and these differences probably reflect non-random sampling rather than a preference on the part of the fish.

Comparisons of temperatures in good and poor rearing grounds showed similar differences for the surface and 10-foot levels in 1952, but fail to indicate any significant differences at the 60- and 40-foot levels in 1953. These comparisons are given in the following tabulation:

Depth	1952	1953
feet		
0	$P < 0.001$	$P \approx 0.55$
10	$P < 0.02$	...
20	$P \approx 0.20$	$P \approx 0.50$
40	$P \approx 0.90$	$P \approx 0.70$
60	...	$P \approx 0.20$

All categories were also compared with respect to their temperature gradients between the surface and 20 feet for the 1952 data, and between the surface and 60 feet for the 1953 data. The results were as follows:

Year	Abundant vs Absent	Present vs Absent	Rearing grounds Good vs Poor
1952	$P > 0.2$	$P > 0.1$	$P > 0.6$
1953	$P > 0.9$	$P > 0.4$	$P > 0.4$

Thus no adequate indication was obtained that the abundance of juveniles was related to temperature gradients.

As was the case for the salinity observations, the 1954 program shifted emphasis to the general temperature picture for the sound. The bathythermograph used in the early part of the survey proved faulty both in the temperature and depth elements, and consequently the data from the first four surveys cannot be considered very reliable. Average temperatures calculated for surveys 5 to 9 were therefore employed in preference to the averages for all surveys (Fig. 11 for the surface and Fig. 12 for depths of 10, 20, 40 and 60 feet).

From the figures it is apparent that juveniles were abundant in localities of both high (Pipestem Inlet, 17.14°C), and low (Banfield Inlet, 13.88°) surface temperatures. Similar ranges of tolerance were shown at 10 feet (Pipestem Inlet, 15.80° and Banfield Inlet, 12.36°), 20 feet (Ucluelet Inlet, 14.16° and Banfield Inlet, 11.70°), 40 feet (Ucluelet Inlet, 13.35° and Banfield Inlet, 11.00°) and 60 feet (Useless Inlet, 12.66° and San Mateo Bay 10.86°). Generally however, the rearing grounds exhibited relatively high temperatures at the surface (15–17°) and 10 feet (14–16°) and relatively low temperatures at 20 feet (12–13°), 40 feet (11–12°) and 60 feet (10.5–11.5°). Although the rearing grounds appeared to have a greater temperature gradient and a sharper thermocline than the other localities (i.e. greater stability), statistical analyses of the 1952 and 1953 data did not indicate this relationship was significant.

Stability, as indicated by variation in temperature with depth, was also investigated in very sheltered, slightly sheltered, and unsheltered localities in which juveniles were relatively abundant. Thermoclines when present, were generally between 5 and 20 feet. The thermocline tended to be at shallower depths in the

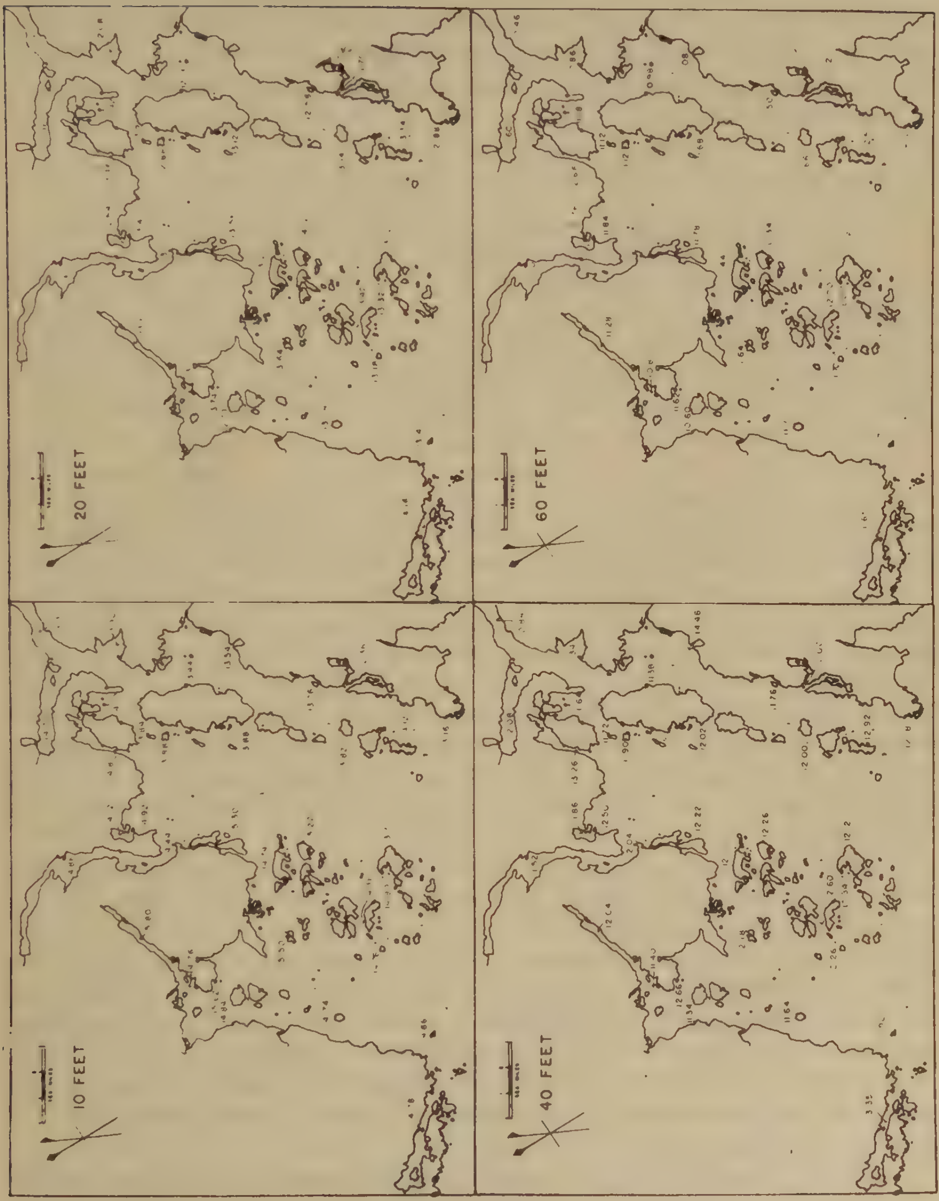
10 FEET
20 FEET
40 FEET
60 FEET

FIG. 12. Average temperatures at depth of 10, 20, 40 and 60 feet at 34 stations in Barkley Sound during 1954.

more sheltered water, and was generally present when fish were observed. Thermoclines were present in some localities when no juveniles were found, but in most cases when no thermocline was observed no fish were present. Thus the presence of a shallow thermocline may be one prerequisite of a good juvenile herring rearing ground. This could concentrate the plankton and make it more accessible to the feeding juveniles. Zooplankton tended to be slightly more abundant at a depth of 15 feet in the bays and inlets populated by juvenile herring than just outside the mouths of these localities.

3. FOOD SUPPLY

As noted in the case for passive movement, volumetric analysis was carried out weekly during the summer on standard samples of the smaller zooplankton taken from a depth of 15 feet at each of 34 stations (Fig. 10). Relatively high concentrations of zooplankton were found in Loudoun and Thiepval Channels (Stations 8, 9 and 10) and, to a lesser extent in Ucluelet Inlet and Macoah Passage (Stations 1, 2 and 3). A relatively high local concentration was also found in Inner Vernon Bay (Station 18). Relatively low concentrations were found in Trevor Channel and Alberni Inlet and most of their adjoining bays (Stations 21, 27, 29, 30, 31, 32, 33, 34). Abundance was also low in Outer Pipestem Inlet (Station 5), Swaile Rock (Station 13), Effingham Inlet (Stations 16 and 17) and Outer Vernon Bay (Station 19). Aside from a few local variations, zooplankton abundance was relatively high in the southwest corner of the sound, and relatively low along the southeast side and in the larger inlets. Generally speaking, this is the opposite trend to that indicated by juvenile abundance (Fig. 2). The only localities in which large populations of both zooplankton and juveniles were found were Ucluelet Inlet (Station 1), Inner Loudoun Channel (Station 8) and Inner Vernon Bay (Station 18). The concentrations of juveniles in Inner Loudoun Channel were sporadic and must be considered as transient fish. Since juveniles were relatively abundant in practically all inlets, the good showing in Ucluelet Inlet and Inner Vernon Bay could not be attributed to the relatively abundant food supply there.

Thus it would not appear that the juveniles adopt their rearing grounds because of the abundance of their food supply. In general zooplankton was less abundant on the rearing grounds than elsewhere. On the other hand, the apparently inverse relationship between zooplankton and juvenile abundance could be the effect of predation. Cushing (1956) suggests the lack of a direct relationship between zooplankton and phytoplankton abundance in English waters results largely from predation by herring on the zooplankton. Riley and Bumpus (1946) have established such a relationship for phytoplankton and their zooplankton predators. A similar situation may therefore apply to the zooplankton-herring relationship in Barkley Sound.

For the sound as a whole, the average displacement volume of these smaller zooplankters was 0.29 cc/m^3. Abundance was greatest in early September when the average for the sound was 0.35 cc/m^3. These figures are low in comparison with zooplankton concentrations estimated for Puget Sound by Hebard (1956) which

(730)

give an annual average for the upper 57 meters of 0.32 cc/m^3 and a peak average in August for the upper 148 meters of 0.73 cc/m^3. However, the maximum zooplankton concentration would certainly occur below 15 feet (LeBrasseur, 1954) so the Barkley Sound estimates should be lower than Hebard's. In addition, coelenterates, ctenophores or other large organisms were removed before the analysis, so that the volumes recorded were those for the smaller organisms only.

A rough sorting of the samples (Table 1) indicated that the bulk of their volume was made up of small Crustacea and Mollusca. The most abundant food organisms found were the zoea larva of the porcellaine crab *Petrolesthes* and small copepods. Since young herring in southern British Columbia waters tend to feed on a considerable variety of small organisms (Wailes, 1935), these samples are assumed to be a fair representation of the amount of food available to the juveniles.

The relatively high productivity of the sound as a whole (Waldichuk, 1956) combined with the relatively low rate of loss of water to the open ocean (Doe, 1952) should tend to make conditions in Barkley Sound on the whole very good for the rearing of juvenile herring. However, food supply may be limited for large year classes of juveniles (Hourston, MS, 1958).

4. SHELTER

After schools had formed early in July, the juveniles were found mainly in inlets and bays and in channels between islands. In most of these places the water was relatively shallow (less than 10 fathoms) and in some (e.g. Ucluelet Inlet) it was extremely shallow (less than three fathoms). One factor these localities had in common was some degree of shelter from prevailing winds and currents. The surface was usually considerably calmer than in more exposed localities. In more open situations fish were observed sporadically, but almost invariably in calm weather. Although visual observations were difficult, if not impossible, when the sea was relatively rough, the echo-sounder failed to show appreciable numbers of fish under these conditions. Even in the sheltered localities the juveniles were usually absent from those portions more disturbed by wind or current. A very striking illustration of this behaviour was encountered in a survey of Burgoyne Bay on the lower east coast of Vancouver Island in 1955 (Hourston, 1956). There were several patches of ruffled surfaces within the bay at the time of survey, and although there were large quantities of juveniles in the bay (the estimated population was 4 million) showing at the surface and on the sounder, the fish abruptly ceased to show, either at the surface or on the sounder, upon entering these rough patches. This phenomenon was observed on every one of 10 such runs. Observations in other localities showed similar phenomena, but less strikingly.

Within the bays and inlets the fish tended to concentrate near shore, especially around docks, log booms, kelp patches and rock piles, presumably because of the shelter these objects provided. As the summer progressed and they grew larger and formed larger schools, the fish tended to move farther offshore, finally moving seaward to desert the bays and inlets from mid-September to late October. Even on the seaward migration they tended to hug the shoreline.

TABLE I. Relative abundance of juvenile herring, and approximate abundance of their probable food organisms (Crustacea and Mollusca) and of dinoflagellates and phytoplankton, in a series of 9 hauls at each of 34 stations in Barkley Sound, 1954. Entries in **bold face** type indicate relatively high abundance.

Station number	Rearing ground rating[a]	Juvenile abundance × 10³	Crustacea					Mollusca			Eggs[c]	Phyto-plankton[c]	Dinofla-gellates[c]
			Clado-cera	Ostra-coda	Cirre-pedia	Cope-poda	Deca-poda	Gastro-poda	Pelecy-poda	Annelida			
1	E	1000	**20–200**	**20–100**	**100–300**	**50–500**	**20–100**	**10–50**	0	0–25	**S–A**	**S–A**	**O–A**
2	P	1000[b]	0–100	0–50	0–100	**50–200**	**10–100**	0–25	10–50	**0–100**	S	**S–A**	**O–A**
3			**0–200**	0–50	0–50	0–100	0–20	0	**0–400**	**0–250**	O–N	**S–A**	**O–A**
4	F	250[b]	**0–200**	0–50	0–50	0–50	**10–50**	**0–50**	**0–100**	**0–100**	O–S	**S–A**	**O–A**
5	E	1300	**0–200**	0–50	**0–200**	**0–400**	**0–50**	0–25	**0–100**	0–50	O–S	O–N	**O–A**
6	G	200[b]	0–50	0–20	0–50	0–50	**10–100**	0–25	0–50	**25–500**	O–S	**O–A**	**O–A**
7	F	2000	**20–200**	0–20	**0–200**	0–100	**10–100**	0–25	0–20	0–50	O–S	**O–A**	**O–A**
8	F	1500[b]	**0–300**	0–20	10–100	**0–300**	**10–700**	0–25	0–20	0–25	O–S	**O–A**	**O–A**
9	P	500[b]	**0–200**	0–20	**20–300**	**100–500**	**10–50**	**0–50**	0–50	0–50	O–S	**S–A**	**O–A**
10	F	1000[b]	**50–400**	0–50	**0–200**	**20–200**	**20–100**	**0–100**	0–50	0–25	S	**O–A**	O–N
11	P	10[b]	**0–500**	0–50	**0–200**	**100–500**	**10–50**	**0–50**	**0–100**	0–10	O–S	**O–A**	**O–A**
12	G	1000	0–100	0–20	**20–200**	**100–300**	2–25	0–20	0–10	0–20	**S–A**	**O–A**	O–N
13	F	70	0–100	0–20	**10–200**	**50–200**	1–20	0–10	0–10	0–20	**O–F**	**O–A**	**O–A**
14	F	1000[b]	**0–200**	0–50	**0–200**	**25–500**	**1–50**	1–50	0–25	0–50	O–N	**O–A**	**O–A**
15	P	0	**0–1000**	0–50	**25–1000**	**10–500**	**0–50**	0–20	0–50	0–20	S–N	**O–A**	**O–A**
16	E	600	**20–500**	0–20	**20–300**	**50–300**	**10–50**	0	0–25	0–50	S–N	**O–A**	O–N
17			**0–500**	0–50	0–100	**20–300**	**10–50**	0–25	0	0–20	**S–A**	S–N	**S–A**
18	E	250	**25–500**	0–50	**0–400**	**25–200**	**20–100**	0–20	**0–100**	0–20	O–N	**O–A**	**O–A**

(732)

TABLE I: *continued*

Station number	Rearing ground rating[a]	Juvenile abundance $\times 10^3$	Crustacea					Mollusca					
			Clado-cera	Ostra-coda	Cirre-pedia	Cope-poda	Deca-poda	Gastro-poda	Pelecy-poda	Annelida	Eggs[c]	Phyto-plankton[c]	Dinofla-gellates[c]
19	P	0	0–100	**0–100**	0–100	0–100	**0–50**	0–50	0–50	0	**O–A**	O–S	O–S
20	E	300	0–100	**0–100**	0–100	0–100	**1–200**	0	0–20	0–25	O–S	**S–A**	O–S
21	G	300	0–50	0–20	0–50	**0–200**	**0–50**	0–20	0–20	0–25	**O–A**	O–S	O–S
22	G	100	0–50	0–50	10–50	10–100	10–20	0	0	0	O–S	**S–A**	O–N
23	P	0	0–50	0–25	0–100	**50–200**	**10–50**	0	0–25	0	O–N	**O–A**	O–N
24	P	0	0–100	0–50	**0–200**	**50–1000**	**10–50**	0–25	0–50	0–25	**O–A**	**O–A**	O–N
25	P	0	0–50	0–20	**20–200**	**50–500**	10–20	0–25	0	0	**S–A**	**S–A**	O–S
26	P	0	0–50	0–20	**0–500**	**50–1000**	10–20	0–20	0–20	0	**S–A**	**O–A**	O–S
27	P	0	0–50	0–10	0–100	**25–500**	1–20	0–20	0–20	0–1	**S–A**	**S–A**	O–S
28	E	600	0–100	0–20	**50–100**	**0–500**	10–20	0–25	0–20	0–25	O–N	O–S	O–N
29	E	2000	20–25	0–20	0–50	**50–500**	**10–50**	0–20	0	0	**O–A**	S	O–N
30	E	1100	0–100	0–50	0–100	**0–200**	0–20	0–20	0–20	0	**O–A**	O–S	O–S
31	F	500	0–50	0–20	0–50	25–100	**10–50**	0–20	0–20	0	**S–A**	O–N	O–S
32	E	1000	0–50	0–20	10–50	**10–400**	0–20	0–20	**0–100**	0–25	**S–A**	O–S	O–N
33	E	900	0–100	0–50	0–50	0–100	**10–75**	0–20	0–50	0	O–S	**S–A**	O–N
34	P	0	0–20	0–20	0–20	0–100	0–10	0–25	**0–100**	0–10	O–N	**O–A**	O–N

[a] E—Excellent; G—Good; F—Fair; P—Poor.

[b] These fish were seen on only some visits.

[c] O—None; S—Scarce; N—Numerous; A—Abundant.

It would therefore appear that during their first summer the juveniles concentrate in bays and inlets and the more sheltered sides of islands (especially in "back-eddies"), where the surface is less disturbed by winds, the currents are relatively weak, and the water relatively shallow. This preference for quiescent conditions could be associated with feeding conditions but is not necessarily so. Young salmon seek such conditions during migration to the sea, apparently for the shelter they offer (F. Neave, personal communication). The fact that there are more localities satisfying these conditions on the southeast side of the sound than on the northwest side may account for the greater concentration of juveniles along the southeast shore.

SUMMARY

During the early juvenile stage, the herring in Barkley Sound move from the spawning grounds, mainly on the northwest side of the sound, to rearing grounds, mainly on the southeast side, where they remain for the summer. This change in distribution could result from (1) *passive transport* of the fish across the sound by prevailing currents (or, indirectly, from passive transport of the zooplankton in this manner with the juvenile herring following their food supply), or (2) *active dispersal or migration* of the young herring from the spawning grounds followed by a *concentration* in the more desirable rearing grounds.

It can be reasonably postulated that the juveniles (or the zooplankton) spend a sufficient portion of their time below the surface layer (down to 3 to 5 fathoms) to be carried by prevailing deep currents to the southeast side of the sound. However, the currents at these depths would tend to continue to carry them up Alberni Inlet. No such movement was indicated by the surveys; on the contrary, the concentrations of juveniles moved slowly but progressively seaward as the summer progressed. Also, if the herring were following their food supply, they effectively reduced it, by predation to a level below that on the northwest side and then failed to take advantage of the relative surplus of food that resulted on the northwest side. Thus an hypothesis of the mechanism of movement based on passive drifting on the part of either the juveniles or their food supply cannot be adequately substantiated.

If the juvenile herring dispersed from the hatching areas and then gradually concentrated in the rearing areas, or if they actively sought out the rearing areas, these areas should have some factor or combination of factors in common that make them more desirable to the juveniles. Most aspects of the environment investigated failed to show any consistent correlation with the abundance of the juveniles. Most habitats consistently favoured by juvenile herring had salinities less than 28‰ but some schools did concentrate in areas of higher salients. Juvenile habitats almost always had shallow thermoclines but such thermoclines were frequent elsewhere. Neither the presence nor the abundance of juveniles was correlated with the salinity or temperature at the depths at which they occur, nor with the depth gradient in these two factors. Habitats frequented by juvenile herring contained lower concentration of the smaller zooplankters on which these fish feed than most other localities in the sound but this difference in the abundance of the food supply could result mainly from predation by the herring. Thus any effect these three aspects of the environment may have had on the distribution of juvenile herring within the sound is obscure and probably secondary.

By elimination, the only one of the factors examined which could account for the observed distribution of juvenile herring is the physically more stable environment found in the sheltered inshore waters of the habitats they favoured. Juvenile herring were consistently present only in the shallow, sheltered waters of bays, inlets and smaller channels where protection from extreme effects of the elements was available. The circumstances that such situations are more numerous on the southeast side of the sound than on the northwest side, along with the fact that more good spawning grounds are found on the northwest side, could provide the impetus for the change in distribution. Juvenile herring are known to wander a great deal and this, combined with the fact that this change in distribution is accomplished over several weeks, indicates that the mechanism is probably dispersal from the spawning grounds followed by gradual concentration in the rearing areas rather than a direct, motivated migration.

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REFERENCES

Buchmann, A., W. Harder and G. Hempel. 1953. Unsere Beobachtungen am Hering (*Clupea harengus* L.). *Kurze Mitteilungen aus der fischereibiologischen Abteilung des Max-Planck-Instituts für Meeresbiologie in Wilhelmshaven*, **3**: 22–42.

Cushing, D. H. 1956. Phytoplankton and the herring. Part V. *U.K. Ministry Agric., Fish. and Food, Fish. Investig.*, Ser. II, **20**(4), 19 pp.

Doe, L. A. E. 1952. Currents and net transport in Loudoun Channel, April, 1950. *J. Fish. Res. Bd. Canada*, **9**(1): 42–64.

Frolander, H. F. 1954. Plankton volume displacement indicator. *Univ. of Washington, Dept. of Oceanogr.*, Tech. *Rept.* No. 25: 13 pp.

Fujita, T., and S. Kokubo. 1927. Studies on herring. *Bull. School Fish., Hokkaido Imperial Univ.*, **1**(1).

Glover, R. S. 1953. The Hardy plankton indicator and sampler: a description of the various models in use. *Bull. Mar. Ecol.*, **4**(26): 7–20.

Hebard, J. F. MS, 1956. The seasonal variation of zooplankton in Puget Sound. M.Sc. thesis, Univ. of Washington, 64 pp.

(735)

HOURSTON, A. S. 1953a. Estimation of herring population size by means of echo-sounder tracings, and its application to herring research. *Fish. Res. Bd. Canada Biol. Sta., Nanaimo, Circ.* No. 26, 76 pp. (Multilithed.)

1953b. The relationship of herring in inshore waters to the temperature and salinity of their environment. *Fish. Res. Bd. Canada, Pac. Prog. Rept.*, No. 96, p. 15.

1957. Relative abundance of juvenile herring in the Strait of Georgia in 1955 and 1956. *Ibid.*, No. 109, pp. 12–13.

1958a. Population studies on juvenile herring in Barkley Sound, British Columbia. *J. Fish Res. Bd. Canada*, **15**(5): 909–960.

MS, 1958b. Plankton production in Barkley Sound in 1954, from approximations of the standing crop of zooplankton and the increase in biomass of its predators. *Fish. Res. Bd. Canada, Ms. Rept. Biol. Sta.*, No. 645, 8 pp. (Multilithed.)

LEBRASSEUR, R. J. MS,1954. The physical oceanographic factors governing the plankton distribution in the British Columbia inlets. M.A. thesis, Univ. of British Columbia, 52 pp.

RILEY, G. A., AND D. F. BUMPUS. 1946. Phytoplankton-zooplankton relationships on George's Bank. *J. Mar. Res.*, **6**(1): 33–47.

SNEDECOR, G. W. 1947. Statistical methods, 4th edition. The Iowa State College Press, 485 pp.

STEVENSON, J. C. MS,1955. Distribution and survival of herring larvae (*Clupea pallasi* Valenciennes) in British Columbia waters. Ph.D. thesis, Univ. of Toronto, 161 pp.

STEVENSON, J. C., A. S. HOURSTON, K. J. JACKSON AND D. N. OUTRAM. 1952. Results of the west coast of Vancouver Island herring investigation, 1951–52. *Rept. British Columbia Fish. Dept.* for 1951, pp. 57–87.

STEVENSON, J. C., A. S. HOURSTON AND J. A. LANIGAN. 1951. Results of the west coast of Vancouver Island herring investigations, 1950-51. *Rept. British Columbia Fish. Dept.* for 1950, pp. 51–84.

STEVENSON, J. C., AND D. N. OUTRAM. 1953. Results of investigation of the herring populations on the west coast and lower east coast of Vancouver Island in 1952-53, with an analysis of fluctuations in population abundance since 1946–47. *Rept. British Columbia Fish. Dept.* for 1952, pp. 57–84.

SVERDRUP, H. U., M. W. JOHNSON AND R. H. FLEMING. 1949. The oceans—their physics, chemistry and general biology. Prentice-Hall, Inc., New York, 1,087 pp.

TAYLOR, F. H. C., AND D. N. OUTRAM. 1954. Results of investigation of herring populations on the west coast and lower east coast of Vancouver Island in 1953–54. *Rept. British Columbia Fish. Dept.* for 1953, pp. 52–82.

TULLY, J. P. 1949. Oceanography and prediction of pulp mill pollution in Alberni Inlet. *Bull. Fish. Res. Bd. Canada*, No. 83, 169 pp.

WAILES, G. H. 1935. Food of *Clupea pallasi* in southern British Columbia waters. *J. Biol. Bd. Canada*, **1**(6): 477-486.

WALDICHUK, M. 1956. Basic productivity of Trevor Channel and Alberni Inlet from chemical measurments. *J. Fish. Res. Bd. Canada*, **13**(1): 7–20.

(736)

UNITED STATES DEPARTMENT OF THE INTERIOR, Fred A. Seaton, *Secretary*
FISH AND WILDLIFE SERVICE, Arnie J. Suomela, *Commissioner*

FOOD OF THE PACIFIC SARDINE (*SARDINOPS CAERULEA*)

By Cadet H. Hand and Leo Berner, Jr.

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(Contribution from Scripps Institution of Oceanography, new series)

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II

FOOD OF THE PACIFIC SARDINE (*Sardinops caerulea*)

By Cadet H. Hand and Leo Berner, Jr.
University of California

Studies of the food of the adult Pacific sardine, *Sardinops caerulea* (Girard), have been limited in scope. Lewis (1929) studied the stomach contents of 207 sardines collected in the San Diego area and found a good relation between surface plankton and the stomach contents of these fish. He concluded that phytoplankton was a very important part of the food, although crustaceans and other zooplankters played a major role in the diet of the sardine.

Parr (1930), in a review of Lewis' data, found that zooplankton in the stomachs showed much less variation in numbers than did the phytoplankton. Using these results he suggested that zooplankters might be the object of special pursuit and the phytoplankton was ingested incidentally.

Hart and Wailes (1931) found a high proportion of diatoms in the stomachs of Canadian sardines collected in 1929, a year of very low oil production per ton of fish. The authors suggest that "red feed" (crustaceans), which makes reduction of the fish more difficult, may in the end, actually lead to higher oil production.

Radovich (1952a) examined the stomachs of 42 fish from central Baja California and southern California. He found that the bulk of the food material consisted of crustaceans, with the copepods dominating. He concluded that sardines are both filter and particulate feeders.

In 1949, the present study of the food of the adult Pacific sardine was begun as part of the Marine Life Research Program. This program is Scripps Institution's component of the California Cooperative Oceanic Fisheries Investigations, a broad study sponsored by the California Marine Research Committee and carried out cooperatively by Scripps Institution of Oceanography of the University of California, the Bureau of Marine Fisheries of the California Department of Fish and Game, the South Pacific Fishery Investigations of the United States Fish and Wildlife Service, the Hopkins Marine Station of Stanford University, and the California Academy of Sciences.

The authors are indebted to John Radovich, California Department of Fish and Game, and to Drs. M. W. Johnson and E. W. Fager of Scripps Institution for their critical reading of the manuscript and many helpful suggestions.

METHODS

The fish from which the stomach samples were obtained were collected along the coast of central Baja California and southern California by the California Department of Fish and Game (see figs. 1 to 3 and table 3). Various methods of collection were used: gill net, beach seine, dip net, and dynamite. The majority of the specimens were collected at night by the latter method. The digestive tracts were removed immediately and preserved in formalin for transport to the laboratory. The earlier collections included digestive tracts alone; later samples were accompanied by plankton samples taken as nearly as possible at the same time and place as the fish. The plankton was collected by a net 0.5 meter in diameter, with a mesh opening of approximately 0.6 mm., hauled vertically in a standard manner. On five occasions, plankton samples were collected from various depth layers. A more complete description of the methods and of the various data taken is given by Radovich (1952b).

In the laboratory, the contents of the oesophagus and stomach, including the caecum, were removed and studied. Originally, the stomachs were analyzed separately; all items in each stomach were counted, or if the amount of material

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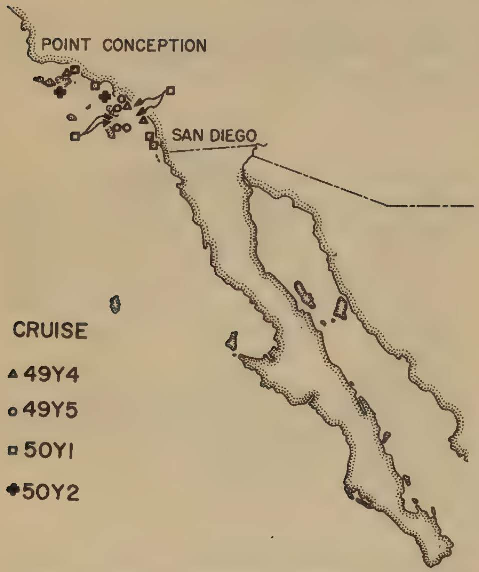

Figure 1.—Location of stations occupied on cruises 49Y4, 49Y5, 50Y1, and 50Y2. Arrows indicate closely spaced stations.

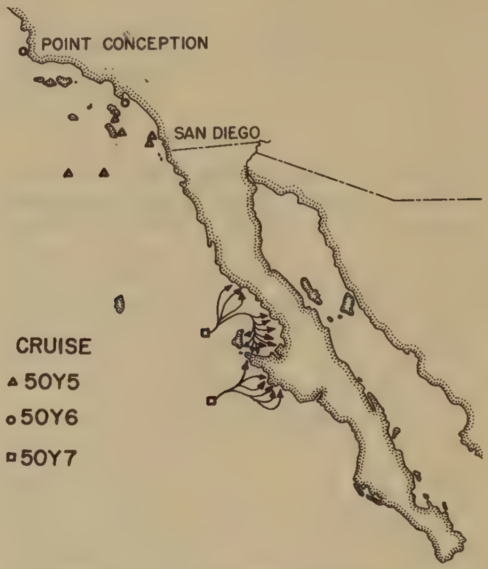

Figure 2.—Location of stations occupied on cruises 50Y5, 50Y6, and 50Y7. Arrows indicate closely spaced stations.

was too great, an aliquot of the contents was counted. After it had been established (as discussed in the next paragraph) that there was no significant variation in stomach contents between fish from the same sample (school), the stomach contents from the individual fish in each sample were combined before counting. A total of 585 stomachs was examined. Most stomachs (571) were from adult fish with standard lengths in the range 110 to 235 mm. The following discussion is based largely on these fish. The stomach contents of 14 small fish, 31 to 85 mm. standard length, were not markedly different from the adults, except for an almost complete absence of phytoplankton (appendix table 3).

In the analysis of the data on food content, it was first pertinent to establish whether or not individuals from the same school had been feeding on the same organisms. If this were found to be true, then it would not be necessary to consider each fish individually. Analysis would be facilitated by combining the stomach contents of fish from the same school. The gross appearance, texture, and color, of stomach contents of fish from single schools were similar and suggested that the fish had been feeding on the same organisms. The stomach contents of fish from seven samples (schools) were compared in detail. Six of the samples contained 10 fish, while the seventh contained 9. Data from a typical sample of 10 fish, 49Y5–2, are given in appendix table 1. Kendall's coefficient of concordance (Siegel 1956, pp. 229–239) was used to test for agreement among the 10 fish in regard to the relative abundances of the different organisms found in the stomachs. This method of analysis, using ranks, is distribution free. The chi-square value obtained ($\chi^2=92.6$ with 12 degrees of freedom) indicates that the probability of the agreement observed between the stomach contents of 10 fish occurring by chance alone is less than 0.001. Comparison of stomach contents within each of the other six samples indicates a similar probability for the agreement to have occurred by chance. On the basis of these data it was decided that stomach samples taken from single schools could be combined and treated as a unit.

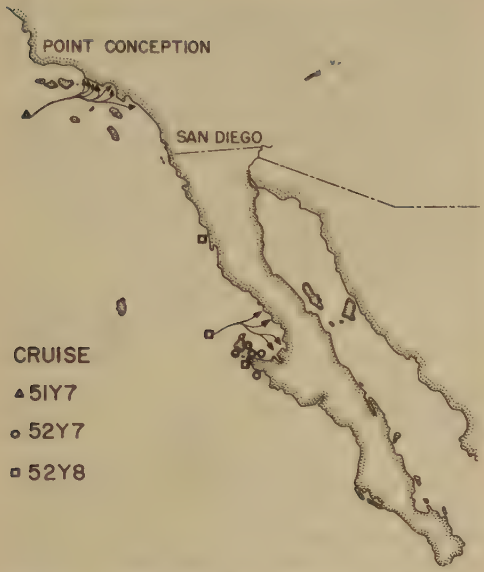

Figure 3.—Location of stations occupied on cruises 51Y7, 52Y7, and 52Y8. Arrows indicate closely spaced stations.

Table 1.—*Frequency of occurrence of various types of organisms found in the stomachs of 273 sardines*

Organism	Percentage occurrence in stomachs
Small copepods	100
Larvaceans	93
Fish eggs	79
Diatoms	75
Chaetognaths	73
Dinoflagellates	71
Large copepods	70
Cladocerans	65
Cyphonautes larvae	64
Euphausiid furcilia and calyptopis larvae	50
Gastropods (adults and larvae)	49
Lamellibranch larvae	48
Copepod nauplii	47
Radiolarians and silicoflagellates	46
Euphausiid nauplii	40
Annelid larvae	36
Euphausiid eggs	32
Zoea larvae	29
Euphausiid adults	24
Amphipods	19
Barnacle nauplii	18
Fish larvae	17
Barnacle cyprids	16
Siphonophores	15
Salps	15
Mysids	13
Copepod eggs	10
Shrimp larvae	8
Brachiopod larvae	4
Ostracods	4
Foraminiferans	3
Doliolids	2
Cumaceans	1
Isopods	1

FOOD OF THE SARDINE

In all, 34 different groups of organisms were identified in the stomach contents. Owing to the semidigested condition of the material and the time involved, it was not considered practical to carry out specific identification.

The types of organisms and their percentage occurrence in the sardine stomachs are listed in table 1.

There is, in general, good agreement between the occurrence of items found in the sardine stomachs and in the plankton. Some marked differences may have resulted from the softer-bodied organisms, such as plutei, annelid larvae, doliolids, and medusae, being quickly digested in the stomachs and losing their identity, and some fast-moving animals, such as euphausiids, eluding the net. In addition, small items, such as copepod eggs and nauplii, were not properly retained by the coarse-meshed net.

Since the numbers of organisms found in the stomachs and in the plankton hauls were of different orders of magnitude, rank correlation (Kendall's tau; Siegel 1956, pp. 213–223), was used in making comparisons. In every case, correlation was very good between plankton hauls in the upper layers of water and in the stomach contents. At five stations it was possible to compare stomach contents with plankton collected at various depths. As might have been expected, correlation was best between fish collected near the surface and plankton collected in the upper layers. The results of these analyses are summarized in table 2.

Table 2.—*Comparison of contents of sardine stomachs and plankton hauls taken at the same time and place*

[Basic data in appendix table 2]

Sample number	Number of items compared	Depth of haul (meters)	Rank correlation coefficient [1]
49Y5-2	16	([2])	+0.508 ($p=0.003$)
50Y1-16	13	([2])	+0.718 ($p=0.0009$)
51Y7-2	18	([2])	+0.302 ($p=0.038$)*
51Y7-12	20	([2])	+0.595 ($p=0.0001$)
50Y2-4	15	0–22	+0.55 ($p=0.002$)
		22–49	+0.33 ($p=0.041$)
		49–77	+0.32 ($p=0.046$)
50Y2-6	17	0–31	+0.552 ($p=0.001$)
		31–68	+0.544 ($p=0.001$)
		68–137	+0.353 ($p=0.023$)
50Y5-5	16	0–62	+0.500 ($p=0.003$)
		67–137	+0.416 ($p=0.012$)
50Y5-9	14	0–28	+0.506 ($p=0.006$)
		28–47	+0.363 ($p=0.034$)
		47–140	+0.157 ($p=0.215$)*
50Y5-13	11	0–62	+0.745 ($p=0.0007$)
		62–140	+0.411 ($p=0.039$)*

*Indicates those values in which tau values were corrected for ties.

[1] Significance level.

[2] From various depths; in general, from sea bottom to the surface.

TABLE 3.—*List of stations with dates, times, and locations of sampling*

Station	Date	Time	Location
49Y5-2	21-XII-49	0145	1 mile off center of Catalina Island.
50Y1-16	16-I-50	2225	6 miles south of Point Loma.
50Y2-4	28-II-50	0830	9.2 miles 323° T. from Point Vincente Light.
50Y2-6	1-III-50	0840	5.9 miles 038° T. from W. Point Santa Cruz Island.
50Y5-5	9-V-50	2140	3.5 miles off Ocean Beach.
50Y5-9	11-V-50	0030	60 Mile Bank.
50Y5-13	12-V-50	0245	32°03′ x 119°48′.
51Y7-2	8-VIII-51	0025	2.5 miles southeast of Newport.
51Y7-12	11-VIII-51	2115	1 mile northeast of Point Dume.

This close correlation between stomach contents and plankton would be expected if the sardine is an omnivorous, filter-feeding fish. As stated previously, Lewis (1929) found good correlation between the sardine stomach contents he examined and plankton samples taken in the same area.

Our data do not allow any precise statement as to the degree of selection of specific food particles as opposed to the filter-feeding activities of sardines. Some stomach contents, not included in this study, indicate that sardines use both methods of feeding in nature and observations in aquariums support this view. Davies (1956) found that South African pilchards (*Sardinops ocellata*) could live as long as 6 months as particulate feeders in aquariums from which all plankton had been removed. He later concluded (1957) that the pilchard is mainly a filter feeder on plankton, but at times may be a particulate feeder. Groody (1952) observed the feeding of sardines of 200 mm. standard length in aquariums. The fish fed almost entirely by filtering. They merely oriented toward a cloud of brine shrimp, increased their swimming speed and, while the cloud was dense, did not select but plunged through it with their mouths open, filtering many shrimp from the water by the action of their gill rakers. Only when the shrimp became extremely scattered did the sardines feed on individual shrimp. During this particulate feeding, no selection of shrimp according to size was observed. Sardines accepted dead brine shrimp. This result, combined with others, led Groody to conclude that the fish found their food by reacting to odor.

Adult sardines feed selectively in nature. Samples have been examined in which the stomachs contained almost exclusively a single food item. In this investigation two particularly unusual observations of stomach contents were noted. In one, the stomachs were filled almost entirely with euphausiids; in the other, fish larvae comprised the sole food item.

The total organic content (food value) of the more common items found in the stomachs is probably a better measure of their relative importance than either frequency or abundance alone. The organic matter contained in the following food was determined by ashing:

Organism	Size (mm.)	Average organic matter/specimen (mg.)	Number of specimens ashed
Small copepods	0.9	0.04	100
Large copepods	1.8	0.07	100
Euphausiids	10.0	0.9	10
Anchovy eggs	0.9	0.1	100
Chaetognaths	13.0	0.1	10

From the literature, the following values were obtained for phytoplankton organisms: Dinoflagellates (*Prorocentrum micans*), 2 × 10^8 cells per gram of dry material (Fox and Coe, 1943); small diatoms 6.75 × 10^8 cells per gram of organic matter (Fox and Coe, 1943); *Calanus finmarchicus*, 0.27 mg. per individual (Marshall, Nicholls, and Orr, 1934). Using these figures, we may estimate the nutritive role of the more prominent elements of the sardines' diet. The following results are based on average stomach contents of 571 fish:

Organism	Average number in 571 stomachs	Total organic matter (mg.)	Total organic matter (percent)
Diatoms	1.14×10^6	4.77	4.9
Dinoflagellates	33,000	0.7	1.9
Small copepods	666	26.64	74.2
Large copepods	20	*3.4	9.5
Euphausiids	2	1.8	5.0
Chaetognaths	9	0.9	2.5
Fish eggs	7	0.7	1.9

*Average of values determined in this study and by Marshall, Nicholls, and Orr (1934).

The inclusion of the other food items found in the stomachs would not appreciably change these percentages. In the 571 stomach contents examined, small copepods, on the average, supplied about 74 percent of the total organic matter, and all crustaceans supplied nearly 89 percent. Since small copepods are so important in the diet of the sardine, a reduction in their numbers or availability might adversely affect the sardine.

The studies of Hart and Wailes (1931) indicated that the sardine in Canadian waters consumed a much higher proportion of phytoplankton. These observations were supported by the study of 68 stomach samples, collected in the fall of 1940, and supplied the authors by Dr. J. L. Hart, then director of the Pacific Biological Station, Nanaimo, B.C. (Unfortunately, the sizes of these fish were not recorded.) All of the stomachs showed a much greater phytoplankton content than any examined from the Baja or southern California area: 23 fish contained over 90 percent phytoplankton, chiefly diatoms, by volume; 36 fish more than 75 percent; 19 fish from 50 to 75 percent, and 13 fish had less than 25 percent phytoplankton. If we accept Parr's hypothesis that phytoplankton is ingested incidentally during filter feeding, the increase in diatoms in the stomachs would be expected if the numbers of diatoms increase to the north. Davies (1957) indicates an apparent preference for phytoplankton as food by the South African pilchard and suggests that the reason for congregation of schools in St. Helena Bay may be the heavy concentrations of phytoplankton in the area. He finds that phytoplankton is eaten in large quantities whenever it is available, but zooplankton is eaten mainly when phytoplankton is scarce. If this is true, Parr's hypothesis cannot be applied to the pilchard in that area.

Brodski and Jankovskaya (1935) in an investigation of the far eastern sardine, *Sardinops melanosticta*, reached much the same conclusions as Parr (1930). They concluded that the presence of diatoms in the sardine stomachs appears to be incidental to the ingestion of copepods. Further, that zooplankton (mainly copepods) is the principal food of the sardine and that phytoplankton is a so-called forced diet in the absence of zooplankton concentrations.

In our material, a comparison of organisms ingested by sardines during night and day feeding has little meaning because of the small number of samples collected during the day. On the basis of our limited data, there does not appear to be any marked difference in food organisms taken in their night and day feeding.

We found very few sardine eggs in the sardine stomachs. During cruise 52Y8, five samples containing 54 sardines in spawning condition were collected from waters that contained sardine eggs. These fish had empty or nearly empty stomachs. In other instances where samples contained fish that were ready, or nearly ready, to spawn but where spawning had not yet occurred, nearly normal amounts of food were found in the stomachs. From these data it appears that sardines in the act of spawning or in the presence of spawning fish stop feeding. In contrast, Davies (1957) reports that the majority of fish eggs in the stomachs of South African pilchard were pilchard eggs.

SUMMARY

The stomach contents of sardines ranging in size from 31 to 285 mm. standard length were examined. Crustaceans were found to be the major food, and within that group small copepods were the most important item. In 571 fish examined, the crustaceans, on the average, contributed 89 percent of the organic matter in the stomachs; the small copepods contributed 74 percent of the total.

Owing to the lack of data on day-feeding fish, only general comparisons could be made between day and night feeding. There does not appear to be any marked difference between the two groups.

With the exception of the smaller amount of phytoplankton in the 31- to 85-mm. fish, the size of fish, within the range investigated, had little effect on the food contained in the stomachs.

Correlation between the stomach contents of fish taken from a single school was very high. The stomach contents also showed a high correlation with plankton samples taken at the same place and time. When plankton was collected from various depths, the correlation was highest in samples collected in the upper layers. These correlations give credence to the often-made statement that sardines are ominvorous, filter-feeding organisms. They do not, however, rule out particulate feeding by the fish.

LITERATURE CITED

Brodski, K. A., and A. J. Jankovskaya.
1935. Contribution to the knowledge of food of the far eastern sardine. Bull. Far East. Br. Acad. Sci. U.S.S.R., No. 13, pp. 102–114. [Translated by A. S. Loukashkin, California Acad. Sci., San Francisco.]

(743)

DAVIES, D. H.
1956. The South African pilchard (*Sardinops ocellata*). Migration 1950–55. Department Commerce and Industries, Div. of Fish., Investigational Report No. 24, pp. 1–52, Pretoria.
1957. The South African pilchard (*Sardinops ocellata*). Preliminary report on feeding off the west coast 1953–56. Department Commerce and Industries, Div. of Fish., Investigational Report No. 30, pp. 147–184.

FOX, D. L., and W. R. COE.
1943. Biology of the California sea-mussel (*Mytilus californianus*). II. Nutrition, metabolism, growth, and calcium deposition. Jour. Exper. Zool., vol. 93, pp. 205–249.

GROODY, T. C.
1952. Behavior studies on the Pacific sardine, *Sardinops caerulea* (Girard). Doctoral dissertation on file in University of California (Berkeley) Library.

HART, J. L., and G. H. WAILES.
1931. The food of the pilchard, *Sardinops caerulea* (Girard), off the coast of British Columbia. Biol. Bd. Canada, Contr. Canadian Biol. and Fish., n.s., vol. 7, No. 19, pp. 247–254.

LEWIS, R. C.
1929. The food habits of the California sardine in relation to the seasonal distribution of microplankton. Scripps Inst. Oceanogr. Bull., Tech. Ser., vol. 2, No. 3, pp. 155–180.

MARSHALL, S. M., A. G. NICHOLLS, and A. P. ORR.
1934. On the biology of *Calanus finmarchicus*. V. Seasonal distribution, size, weight, and chemical composition in Loch Striven in 1933, and their relation to phytoplankton. Jour. Mar. Biol. Assoc. United Kingdom, vol. 19, No. 2, pp. 793–828.

PARR, A. E.
1930. Is the presence of phytoplankton in the stomach contents of the California sardine caused by special pursuit or merely due to incidental ingestion? Ecology, vol. 11, No. 2, pp. 465–468.

RADOVICH, JOHN.
1952a. Food of the Pacific sardine, *Sardinops caerulea*, from central Baja California and southern California. California Fish and Game, vol. 38, No. 4, pp. 575–585.
1952b. Report on the young sardine, *Sardinops caerulea*, survey in California and Mexican waters, 1950 and 1951. California Department Fish and Game, Bureau of Marine Fisheries, Fish Bull. 87, pp. 31–63.

SIEGEL, S.
1956. Nonparametric statistics for the behavioral sciences. McGraw-Hill Book Co., New York, 312 pp.

APPENDIX

Appendix Table 1.—*Stomach contents of 10 female sardines taken from one school, by length and age*

[Sample No. 49Y5-2]

Organism	Number of organisms in stomach of fish measuring—										Number found in plankton tow
	235 mm. (4 yr.)	224 mm. (3 yr.)	217 mm. (4 yr.)	224 mm. (3 yr.)	228 mm. (3 yr.)	217 mm. (4 yr.)	217 mm. (3 yr.)	222 mm. (4 yr.)	225 mm. (3 yr.)	223 mm. (3 yr.)	
Large copepods	30	50	...	4	2	...	15	...	10	...	40
Small copepods	2, 180	1, 615	16, 020	1, 005	648	1, 510	1, 490	596	740	510	2, 250
Euphausiids	40	15	80	10	...	30	25	...	10	15	...
Euphausiid calyptopis larvae	20	30	160	15	8	...	25	4	10	5	40
Euphausiid furcilia larvae	10	...	40	...	4	10	20	2	5	20	...
Euphausiid nauplii	...	...	...	...	4	...	...	...	...	...	30
Euphausiid eggs	240	155	220	105	2	220	130	22	90	195	90
Cladocera	...	...	...	...	...	...	...	...	...	5	...
Cyphonautes	...	...	...	...	...	...	...	2	...	...	20
Larvaceans	380	145	460	145	138	350	220	148	195	380	1, 810
Chaetognaths	...	...	...	...	2	...	10	2	...	20	20
Fish eggs	...	...	...	...	3	...	15	12	15	10	30
Gastropods (adult and larvae)	...	...	...	...	4	10	5	4	5	5	50
Annelid larvae	...	...	...	...	...	...	...	...	...	...	10

Appendix Table 2.—*Comparison of items in stomach contents of sardine samples and in plankton samples taken at same place and time, by samples*

[Absolute numbers of organisms not compared, but used only to establish rank]

Organism	Number of organisms in—							
	Sample No. 49Y5-2		Sample No. 50Y1-16		Sample No. 51Y7-2		Sample No. 51Y7-12	
	Stomach contents	Plankton sample	Stomach contents	Plankton sample	Stomach contents	Plankton sample	Stomach contents	Plankton sample
Large copepods	11	40	13	90	+	120	+	...
Small copepods	2, 730	2, 250	394	2, 170	340	2, 140	542	5, 270
Copepod nauplii	...	...	780	(*)	...	...	248	100
Euphausiids	23	...	...	...	...	...	...	...
Euphausiid calyptopis larvae	28	40	...	...	5	10	4	40
Euphausiid furcilia larvae	11	...	...	...	+	...	+	10
Euphausiid nauplii	+	30	...	...	18	110	2	50
Euphausiid eggs	140	90	...	...	...	120	...	...
Cladocerans	1	...	9	140	+	10	8	100
Cyphonautes	+	20	2	40	5	30	22	140
Barnacle nauplii	...	...	4	30	9	30	4	90
Zoea larvae	...	...	2	10	+	20	...	+
Larvaceans	260	1, 810	44	120	388	1, 560	180	2, 040
Chaetognaths	3	20	6	60	10	30	6	140
Amphipods	...	...	...	...	...	...		
Fish eggs	6	30	6	30	9	60	14	+
Gastropods	3	50	...	...	...	30	12	180
Lamellibranch larvae	...	...	1	...	...	30	12	40
Annelid larvae		10	3	60	8	10	4	30
Number of fish in sample	10	...	10	...	10	...	10	...
Average length of fish	223 mm.	...	192 mm.	...	198 mm.	...	208 mm.	...

+ Present, but average number less than 1.
* Not sampled by plankton net because of small size.

Appendix Table 2.—*Comparison of items in stomach contents of sardine samples and in plankton samples taken at same place and time, by samples*—Continued

Organism	Number of organisms in—						
	Sample No. 50Y5-9				Sample No. 50Y5-13		
	Stomach contents	Plankton (closing-net) sample from—			Stomach contents	Plankton (closing-net) sample from—	
		0-28 m.	28-47 m.	47-140 m.		0-62 m.	62-140 m.
Large copepods	19	130	+	35	2	20	20
Small copepods	52	1, 270	190	155	16	400	90
Copepod nauplii							
Euphausiids	14	10				+	+
Euphausiid calyptopis larvae	77	110	+		1	15	+
Euphausiid furcilia larvae	40	80			2	5	+
Euphausiid nauplii				10	1	5	
Euphausiid eggs	3	30	10	5			
Cladocerans							
Cyphonautes							
Barnacle nauplii							
Zoea larvae							
Larvaceans	28	2, 470	95	20	9	205	45
Chaetognaths	7	100	10	20	3	20	30
Amphipods	+	+	+			5	+
Fish eggs	+	+			26	40	
Gastropods				+			
Lamellibranch larvae							
Annelid larvae		10				5	5
Number of fish in sample	10				10		
Average length of fish	212 mm.				212 mm.		

Organism	Number of organisms in—										
	Sample No. 50Y2-4				Sample No. 50Y2-6				Sample No. 50Y5-5		
	Stomach contents	Plankton (closing-net) sample from—			Stomach contents	Plankton (closing-net) sample from—			Stomach contents	Plankton (closing-net) sample from—	
		0-22 m.	22-49 m.	49-77 m.		0-31 m.	31-68 m.	68-137 m.		0-62 m.	62-137 m.
Large copepods	9	10	5	5	20	90	75	115	672	4, 260	260
Small copepods	209	228	209	257	123	1, 700	875	725		20	
Copepod nauplii	8		1	1	3	120					
Euphausiids				1				5			
Euphausiid calyptopis larvae	7	7	18	12						+	
Euphausiid furcilia larvae	9	4	7	34	1	20	10			10	+
Euphausiid nauplii									48	350	40
Euphausiid eggs					13	800	60	385	38	220	5
Cladocerans	3	4	4		1	60		5		190	
Cyphonautes	3	2	1						12	30	
Barnacle nauplii											
Zoea larvae			2	1						+	5
Larvaceans					14	620	60	15			
Chaetognaths			3	6		10	30	10	24	80	30
Amphipods		3	11	10						+	5
Fish eggs	8	3	3	1					28	100	10
Gastropods		2	4	2		30	5	10		10	
Lamellibranch larvae					1		5		4	+	
Annelid larvae			3	2		10	5				
Number of fish in sample	10				4				10		
Average length of fish	207 mm.				208 mm.				190 mm.		

+ Present, but average number less than 1.

APPENDIX TABLE 3.—*Stomach contents of small (less than 100 mm.) sardines*

A. Sample number, 51Y8-21; time, 0200 PST, date, 30 August 1951; location, 26°58.2′ N., 113°36.2′ W.

Organism	Number of organisms in fish measuring—			
	31 mm.	31 mm.	77 mm.	72 mm.
Small copepods	8	15		4
Large copepods			1	3
Barnacle cypris larvae		2		
Zoea larvae				2
Fish eggs			1	
Moth (Lepidoptera)[1]			1	
Diatoms				(2)
Dinoflagellates	2			(2)

B. Sample number, P44-16; time, 1930 PST; date, 12 January 1953; location, 27°50.2′ N., 114°50.5′ W.

Organism	Number of organisms in fish measuring—				
	46 mm.	46 mm.	51 mm.	49 mm.	55 mm.
Small copepods	3	5	500	12	11
Large copepods		1	4		
Zoea larvae	1	1	7	1	
Chaetognaths		1			
Barnacle nauplius larvae		1			
Barnacle cypris larvae	1	1		1	3
Lamellibranch larvae		2	5		1

APPENDIX TABLE 3.—*Stomach contents of small (less than 100 mm.) sardines*—Continued

C. Sample number, 50Y9-33; time, 2235 PST; date, 11 September 1950; location, 32°47.6′ N., 118°24.3′ W.

Organism	Number of organisms in fish measuring—				
	49 mm.	56 mm.	71 mm.	68 mm.	85 mm.
Small copepods	117	9	260	190	265
Large copepods	12		21	15	18
Cyphonautes larvae	14		48	87	112
Barnacle cypris larvae	3		7	2	16
Fish eggs	1		2	1	
Amphipods	2		1		1
Euphausiids			3	1	2
Zoea larvae			1		2
Diatoms					1,500
Dinoflagellates			6	+	75

+ Present, but average number less than 1.

[1] This food item cannot be considered natural, but only a very chance occurrence.

[2] Present in very small numbers—not counted.

APPENDIX TABLE 4.—*Summary of items in stomach contents of 571 sardines and in plankton samples, by month, November 1949 to September 1952*

[Asterisk (*)—specimens not properly sampled by net; NS—groups not sampled by net. Values given in each column are average number per month]

Organism	Number of organisms in—							
	Sample No. 49Y4 (Nov. 1949)		Sample Nos. 49Y4 and 49Y5 (Dec. 1949)		Sample No. 50Y1 (Jan. 1950)		Sample No. 50Y2 (Feb. 1950)	
	Stomach contents	Plankton sample[1]	Stomach contents	Plankton sample	Stomach contents	Plankton sample	Stomach contents	Plankton sample
Large copepods*	+		7	36	10	27	9	10
Small copepods	2,900		1,203	2,278	205	2,903	209	228
Copepod nauplii*	105		314	15	122	78	8	
Copepod eggs*	1		+		125			
Euphausiids*			7	1				
Euphausiid calyptopis larvae*	+		8	19	+	4	7	7
Euphausiid furcilia larvae			4	4	+	6	9	4
Euphausiid nauplii			+	53	+	1		
Euphausiid eggs			40	29	+			
Cladocera	8		8	45	4	108	3	4
Cyphonautes	3		4	24	9	91	3	2
Barnacle nauplii	1				+	4		
Zoea larvae	+				1	2		
Larvaceans	2		107	818	51	450		3
Chaetognaths	10		23	23	8	29		
Gastropods	2		4	45	+	12		2
Lamellibranch larvae	6		2	1	7	16		
Fish eggs	+		7	41	2	7	8	3
Diatoms*	1,369		27,246	NS	2.6×10^6	NS	5,330	NS
Dinoflagellates*	2,025		6,739	NS	21,915	NS		NS
Radiolaria and silicoflagellates*	121		1,019	NS	1,540	NS		NS
Average volume of food per fish	1.2 ml.		2.1 ml.		0.9 ml.		0.4 ml.	
Number of fish	15		38		81		10	

+ Present, but average number less than 1.

[1] No plankton collected.

APPENDIX TABLE 4.—*Summary of items in stomach contents of 571 sardines and in plankton samples, by month, November 1949 to September 1952*—Continued

Organism	Number of organisms in—							
	Sample No. 50Y2 (Mar. 1950)		Sample No. 50Y5 (May 1950)		Sample No. 50Y6 (June 1950)		Sample No. 50Y7 (July 1950)	
	Stomach contents	Plankton sample	Stomach contents	Plankton sample	Stomach contents	Plankton sample [1]	Stomach contents	Plankton sample [1]
Large copepods*	20	90	33	74	80		42	
Small copepods	123	1,700	310	1,324	6,200		390	
Copepod nauplii*	3	120	57	80	122		130	
Copepod eggs*								
Euphausiids*			4	3	1		4	
Euphausiid calyptopis larvae*			14	31	7		11	
Euphausiid furcilia larvae	1	20	8	18	1		9	
Euphausiid nauplii			11	66	1		7	
Euphausiid eggs	13	800	9	45	1			
Cladocera	1	60	12	33	635		41	
Cyphonautes			2	5			7	
Barnacle nauplii							1	
Zoea larvae				2			3	
Larvaceans	14	620	480	1,059	65		104	
Chaetognaths		10	16	58	5		9	
Gastropods		30	+	2			3	
Lamellibranch larvae	1		1	+			2	
Fish eggs			20	37	33		4	
Diatoms*	4.5 x 10^6	NS	8.3 x 10^5	NS	21 x 10^6		97,000	
Dinoflagellates*	52,000	NS	13,000	NS	6.5 x 10^5		27,000	
Radiolaria and silicoflagellates*		NS	875	NS	7,000		3,307	
Average volume of food per fish	1.0 ml.		2.1 ml.		1.0 ml.		1.0 ml.	
Number of fish in sample	4		63		12		164	

Organism	Number of organisms in—						Average number of organisms per fish	Average number of organisms per plankton tow	Percentage of stomachs containing organism
	Sample No. 51Y7 (Aug. 1951)		Sample No. 52Y7 (Aug. 1952)		Sample No. 52Y8 (Sept. 1952)				
	Stomach contents	Plankton sample	Stomach contents	Plankton sample [1]	Stomach contents	Plankton sample			
Large copepods*	3	102	12		1	2	20	49	61
Small copepods	410	6,676	2,180		167	557	666	2,238	92
Copepod nauplii*	79	15	1,180		188	817	254	161	47
Copepod eggs*							18	NS	10
Euphausiids*	+	1					2	1	21
Euphausiid calyptopis larvae*	2	21					6	12	33
Euphausiid furcilia larvae	+	10	3				4	9	37
Euphausiid nauplii	3	44					4	23	18
Euphausiid eggs	8	129					5	143	15
Cladocera	3	37	48		68	41	39	47	53
Cyphonautes	11	105	2		+	3	6	33	44
Barnacle nauplii	3	39					1	6	12
Zoea larvae	1	9	+			8	1	3	26
Larvaceans	111	1,792	108		11	98	126	691	71
Chaetognaths	5	180	11		5	73	9	53	69
Gastropods	3	100	3		4	3	2	28	37
Lamellibranch larvae	2	24	6		+	7	3	7	35
Fish eggs	5	21	9			6	7	16	51
Diatoms*	1.1 x 10^6	NS	64,200		71,600	NS	1.1 x 10^6	NS	65
Dinoflagellates*	20,000	NS	38,000		10^4	NS	33,000	NS	64
Radiolaria and silicoflagellates*	223	NS	504			NS	544	NS	35
Average volume of food per fish	1.0 ml.		0.8 ml.		0.3 ml.		1.1 ml.		
Number of fish in sample	67		67		50				

+ Present, but average number less than 1.

[1] No plankton collected.

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GEOGRAPHY

Evidence of a South Equatorial Countercurrent in the Pacific Ocean

An eastward-flowing current of speeds from 10 to 25 cm./sec. is indicated along a density surface ($\sigma_t = 26{\cdot}81$) in the Pacific Ocean south of the equator in a position roughly symmetrical to that of the (North) Equatorial Countercurrent. Along this surface the current is found between lat. 2° S. and 5° S. at long. 165° E. and progressively farther south toward the east, to between lat. 10° S. and 14° S. at long. 95° W. The depth of this surface rises to the south along the flow, from 400 to 300 m. in the west and from 400 to 350 m. in the east.

The evidence lies in the calculations of geostrophic flow along this surface with respect to 1,000 decibars[1]. The eastward geostrophic flow is indicated on ten cross-sections made by the *Equapac* expeditions (joint surveys carried out by agencies from France, Japan and the United States) in late summer of 1956, on three sections made by the *Carnegie* cruise of 1929–30, ref. 2, and by combinations of stations from the *Carnegie*, *Eastropic*[3,4] and *Downwind* (Univ. of Calif. Scripps Inst. of Oceanogr., unpublished reports) expeditions.

On this surface the path of the eastward flow coincides with a tongue of high salinity extending eastward from a maximum value in the Coral Sea.

North of the equator the (North) Equatorial Countercurrent is indicated on the same density surface by calculations of geostrophic flow. The depth of the surface rises to the north from more than 400 m. at the equator to a ridge of depth less than 300 m. at lat. 5° N., long. 135° E. The ridge extends eastward to lat. 10° N. long. 145° W. at less than 300 m. It continues from there to lat. 5° N., long. 115° W., where its depth is about 350 m. The eastward flowing current is evident on this surface between lat. 2° N. and 5° N. in the west, from lat. 4° N. to 8° N. in the central ocean, and from lat. 5° to 10° N. at long. 120° W., and is indicated on all of the *Equapac* sections and the pertinent *Carnegie* and *Eastropic* sections all the way to the coast of America. Direct measurements[4] made recently in the eastern Pacific have revealed that the eastward flow extends to at least 1,000 m. at long. 107° W.

There is evidence of an eastward flow at the sea surface south of the equator in the measurements of geostrophic flow made on the *Equapac* expeditions by the research vessels *Orsom III* (Institut Français d'Oceanie, New Caledonia, unpublished report) at

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lat. 9° S. between long. 170° and 180° E., where speeds as high as 15 cm./sec. are indicated, and by the *Hugh M. Smith*[5] at the same latitude between long. 169° W. and 135° W., with speeds as high as 8 cm./sec. indicated. Of the other *Equapac* lines, none reached so far as lat. 10° S. except one at long. 164° by the *Horizon* (Univ. of Calif. Scripps Inst. of Oceanogr., unpublished reports) and this was so near the Solomon Islands that the geostrophic calculations, which did indicate an eastward flow, might have other interpretations.

In a combination of stations from the *Carnegie* expedition and the *Eastropic* expeditions of 1955 and the *Downwind* expedition, a weak easterly flow may be interpreted so far east as long. 95° W., but the observations are sparse and the feature is very poorly defined.

In the western Pacific, other evidence for the eastward flow at the sea surface may be found in various atlases prepared from observations of set and drift of vessels. The British average[6] of set and drift for the seasons November–January and February–April indicate a weak eastward flow at lat. 10° S. from long. 165° E. to 140° W. and from long. 165° E. to 165° W., respectively. No evidence is found in other months, and it is to be noted that the *Equapac* observations were made in August. The more recent Netherlands[7] monthly current charts show easterly flow along lat. 10° S. from long. 165° to 180° E. in February, March and April. The American[8] monthly charts show almost no evidence in any month.

The east-flowing current was encountered while studying the distribution of temperature, salinity, and oxygen along the density surface σ_t 26·81, which lies in the intermediate water in the North Pacific and above the intermediate water of the South Pacific. This study is not yet completed, and further information about the flow at other depths and along other surfaces will be obtained as the work progresses.

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May 6.

[1] Montgomery, R. B., *Bull. Amer. Meteor. Soc.*, **18**, 210 (1937).

[2] Fleming, J. A., Ennis, C. C., Sverdrup, H. U., Eaton, S. L., and Hendrix, W. C., Carnegie Inst. Wash., Pub. No. 545, Oceanogr. I-*B* (1945).

[3] King, J. E., Austin, T. S., and Doty, M. S., U.S. Fish Wildlife Serv. Spec. Sci. Rep., Fish. No. 201 (1957).

[4] Knauss, J. A., and Pepin, R., *Nature*, **183**, 380 (1959).

[5] Austin, T. S., U.S. Fish Wildlife Serv. Spec. Sci. Rep., Fish. No. 217 (1957).

[6] M.O. 435, Marine Div. Meteor. Off., Air Ministry, London (1939).

[7] Koninklijk Nederlands Meteorologisch Institut, No. 124 (1949).

[8] U.S. Navy Hydrographic Off., Misc. No. 10,058 (1944).

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Thermal Changes Accompanying the Compression of Aqueous Solutions to Deep-Sea Conditions[1]

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ABSTRACT

Apparatus is described for studying the effects of high hydrostatic pressure on the viability, reproduction, and physiological reaction rates of bacteria in aqueous solutions. Rapidly compressing such solutions to deep-sea conditions results in temperature increases ranging from 2 to 5°C. Decompressing the system to ambient pressure results in cooling to a corresponding degree. When the apparatus is submerged in constant temperature water bath, the thermal time constant T-63 of solutions compressed or decompressed in the steel pressure vessel is generally less than 3 minutes. The degree of heating or cooling is primarily a function of the change in hydrostatic pressure and the ambient temperature. To a lesser extent heating or cooling is influenced by the chemical composition of the solution. The degree and duration of thermal changes may be minimized by the use of small pressure vessels submerged in constant temperature bath and by slow compression or decompression. Thermal changes were measured by bead-type thermistors, which must be calibrated for use at each pressure and ambient temperature.

INTRODUCTION

Hydrostatic pressures of a few hundred atmospheres influence the multiplication, viability, and metabolic activities of bacteria and allied microorganisms (ZoBell and Johnson 1949, ZoBell and Oppenheimer 1950, and Kitching 1957). Such effects may be appreciable in the sea where pressure approaches 1100 atmospheres in the greatest known deeps (Wüst 1951, Carruthers and Lawford 1952). Some of the effects of deep-sea pressures on apparatus have been described by ZoBell (1954). Hydrostatic pressure in the sea increases with depth by approximately 0.1 atm/m, the pressure-depth gradient being influenced only slightly by latitude, salinity, or by temperature (Bjerknes and Sandström 1910). One atmosphere is equivalent to 14.696 lb/in^2 (psi), 1.0332 kg/cm^2, 1.0133 bars, or to 760 mm Hg at 0°C.

Since biochemical reaction rates are extremely sensitive to temperature changes, and since the biological effects of pressure are influenced by temperature, it is of utmost importance that the temperature of experimental material be controlled and known. Near the threshold of pressure-temperature tolerance of a biological system, temperature changes resulting from changing pressure may be critical. Controlling the temperature during the compression or decompression of experimental material is complicated by adiabatic heating or cooling. According to Ekman's computations (Sverdrup *et al.* 1942), the heat of compression in the sea ranges from 0.016 to 0.209°C per 100 atm, depending upon the salinity, temperature, and depth of the water. The heat of compression is the heat which flows out of the liquid as it is compressed isothermally.

The heat of compression of complex experimental apparatus employed for investigating the effects of hydrostatic pressure on biological systems cannot be computed from theoretical consideration owing to the anomalous behavior of the heterogeneous components (steel, glass, water, solutes, etc.). If applied adiabatically, the heat of compressing the average biological liquid to 1000 atm would be sufficient to raise its temperature several degrees, the exact rise being a

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function of the ambient temperature and the composition of the liquid. In actual practice the temperature change during the compression of experimental material is less than adiabatic, because of the thermal behavior of the vessel itself and the dissipation of heat to the surroundings. As pointed out by Dorsey (1940), it is extremely difficult to obtain accurate dynamic or experimentally observed values on the thermal properties of water at different pressures owing to the effects of the enclosing and measuring apparatus. The calculation of static or theoretical values for the heat of compression of water is complicated by the concurrent effects of compression on volume, specific heat, conductivity, and molecular species. Tammann and Elbrächter (1931) were unable to explain differences between the static (computed) and dynamic (observed) values on the decrease of water temperature on adiabatic expansion. The compressibility of water is a function of temperature, its relative volume when compressed to 1000 kg/cm² being 0.9567 at 0°C, 0.9741 at 50°C, and 0.9984 at 95°C as compared to a volume of 1.000 under standard conditions (Bridgman 1931).

Therefore, efforts have been made to measure temperature changes which result from pressure changes in experimental materials rather than to measure the heat of isothermal compression. The steel pressure vessels, described below, were kept in a constant temperature water bath during compression and decompression in order to dissipate heat as rapidly as possible as in routine experimental operations. The temperature of aqueous solutions in vessels was recorded continuously at pressures up to 1000 atm and at ambient temperatures ranging from 5 to 55°C. The setup and manipulations in all details simulated the conditions employed in studying the effects of pressure on biological systems.

DESCRIPTION OF APPARATUS

Although designed primarily to study the effects of deep-sea pressures on the viability, reproduction, and biochemical reaction rates of microorganisms, the apparatus has also proved to be useful for investigating the pressure tolerance of lenses, light globes, electromagnets, insulating materials, and other apparatus. The pressure vessel (Fig. 1) is constructed of 18-8 type 303 stainless steel. Such steel has been selected as the best practical compromise among the requisite properties, including relatively high tensile strength with some elasticity, machinability, and chemical inertness or resistance to corrosion.

A vessel having an inside diameter of 1⅜ in. and 11 in. long holds 25 10 x 25-mm stoppered culture tubes and weighs less than 15 lb. Pressure vessels of greater capacity have been fabricated from steel cylinders of greater length or of greater diameter, but the larger ones are rather unwieldy and heat of compression is dissipated more slowly. When the internal diameter of the pressure vessel is increased, it is necessary to increase the wall thickness or external diameter according to the formula of Lamé (Laurson and Cox 1954):

$$S = P\frac{R^2 + r^2}{R^2 - r^2}$$

where S is the tensile strength of the structural material, P is the internal pressure, R is the outer radius, and r is the inner radius. Hamann (1957) expresses the yield pressure of thin walled cylinders simply as $P = (K-1)S$, where K is the ratio of outer to inner radius. We have in use a hundred vessels like the one illustrated in Figure 1, which have been tested at pressures up to 2000 atm.

When properly fitted with an O-ring, the cap can be screwed on by hand to give a pressure-tight seal without the use of a wrench. It may be necessary to use a Stilson or strap wrench, however, to remove the cap after the vessel has been subjected to high pressure owing to the extrusion of the O-ring into the crack between the cap and vessel top. The smooth machine finish at the top of the vessel and the groove which accommodates the 7/64-in. O-ring must be machined with a precision of ±0.005 in. Otherwise minute valleys may permit the O-ring to be extruded all the way through with a resultant loss of hydraulic fluid and

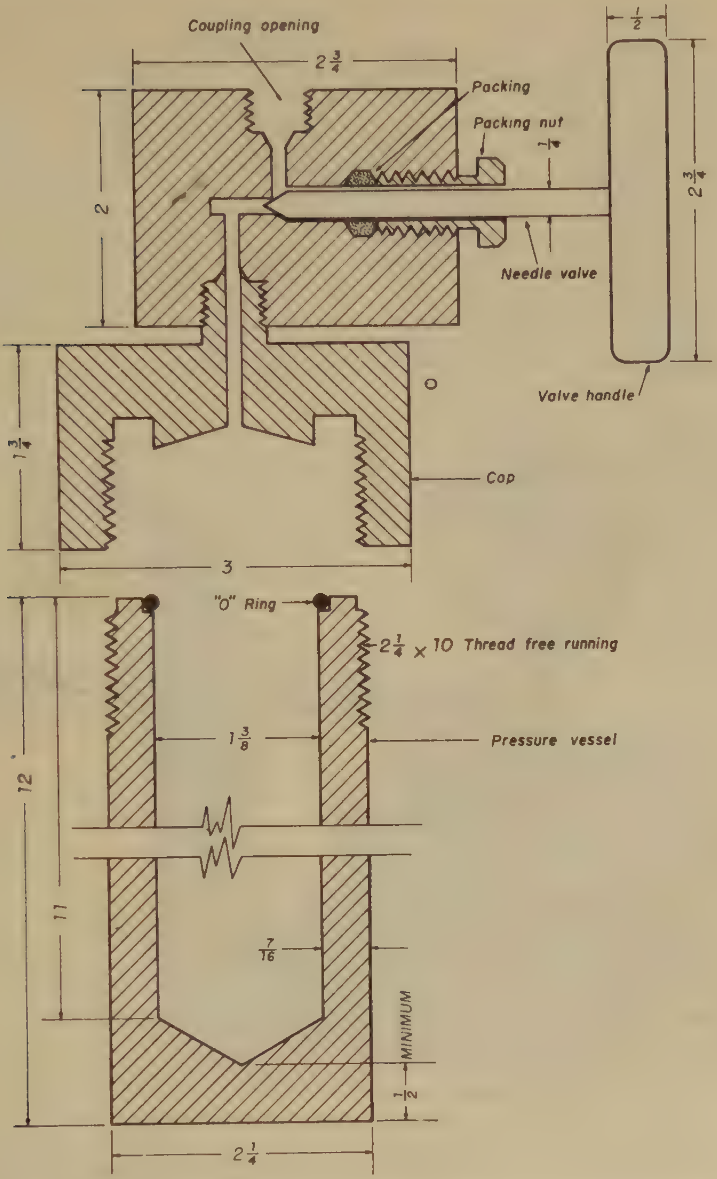
Coupling opening
2 3/4
Packing
Packing nut
1/2
2 3/4
2
Needle valve
Valve handle
O
1 3/4
Cap
3
"O" Ring
2 1/4 x 10 Thread free running
1 3/8
Pressure vessel
12
11
7/16
MINIMUM
1/2
2 1/4

FIG. 1. Cross section of pressure vessel showing cap and needle valve.

pressure. Similarly, a particle of grit, sand, broken glass, or other solid object may keep the cap from coming sufficiently close to the top of the vessel with resultant failure at high pressure. With ordinary precautions, however, such failures are rare. In thousands of cases it has been our experience that when a properly closed vessel holds high pressure initially, constant pressure is maintained thereafter almost indefinitely, provided the temperature is kept constant.

O-rings of various sizes and compositions

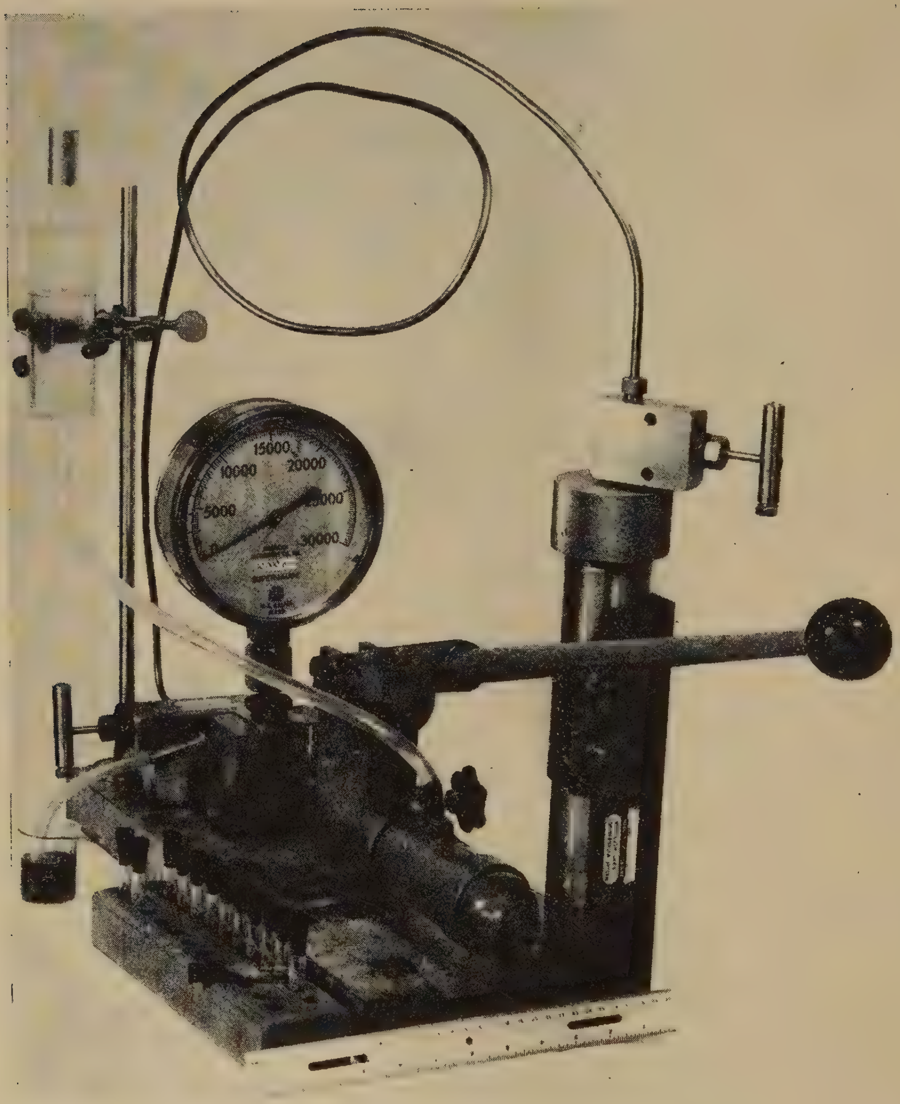

Fig. 2. Assembled pressure vessel connected to hydraulic pump and connecting gauge. Hydraulic fluid flows by gravity from the transparent reservoir into the pump. Beside the assembly is a rack for 10 x 50 mm culture tubes.

are obtainable from Parker Appliance Co., Cleveland, Ohio. The 165-degree funnel-shaped ceiling in the center of the cap is for the dual purpose of securing the O-ring and of expelling gas from the vessel. It is so designed that when the vessel is filled to the rim with hydraulic fluid, the fluid will be forced through the opening in the cap and to the top of the coupling opening in the needle valve without overflowing when the cap is screwed firmly in place.

The threaded male extension at the top of the cap accommodates a stainless steel superpressure needle valve of the type manufactured by American Instrument Co., Silver Springs, Maryland. Each cap is fitted with a valve. The 59-degree conical tip at the top of the cap fits a corresponding 60-degree female conical seat in the valve, which when seated with a wrench gives a pressure-tight joint. The same union-type joint is employed to connect the assembled pressure vessel to the hydraulic pump (Fig. 2) with an appropriate length of stainless steel pressure tubing (o.d. ¼ in. x i.d. ³⁄₃₂ in.).

Figure 2 shows the complete apparatus, including a rack of 10 x 25-mm stoppered culture tubes of the type that are placed inside the vessel. This portable apparatus can be clamped to a work bench in the field, aboard a ship, or in the laboratory.

In the following experiments, designed to determine the heat of compression of biological materials under different conditions, the pressure vessel was kept completely submerged in a constant temperature water bath. It was secured in the vertical clamp, as pictured in Figure 2, only for the purpose of connecting it to the tubing and pump.

Pressures up to 1000 atm (about 15,000 psi), such as occur at a water depth of 10,000 meters, were applied to the vessel in about 30 seconds by several strokes with the pump handle. Hydraulic pumps distributed by American Instrument Co. or by Fred S. Carver, Inc., Summit, New Jersey, have given satisfactory service. Our preference, though, is for large capacity (30-ton) truck jack pumps manufactured by Blackhawk Mfg. Co., Milwaukee 46, Wisconsin. Shown in Figure 2 is a modified truck jack pump connected with a pressure gauge, a system of bleeder valves, and a reservoir of hydraulic fluid. A 1:1 mixture of glycerol and water makes a satisfactory hydraulic fluid. Glycerol is easier to remove from experimental material than oils commonly recommended for use in high pressure pumps. Moreover, the diluted glycerol is less likely to attack rubber packings.

The temperature on the inside of the pressure vessel was measured with a Western Electric Co. 14-B bead-type thermistor. The thermistor (Becker *et al.* 1947) is a glass-enclosed, semiconducting bead of metallic oxides whose resistance is a function of the ambient temperature. It was connected with special insulated leads through the cap of a pressure vessel (Fig. 3) to a Wheatstone bridge and a Leeds & Northrup type-G Speedomax recorder, calibrated to record the temperature continuously. In later work a Varian model G-11 strip chart recorder gave equally good results. Calibration values at specified temperatures from 5 to 55°C and at pressures up to 1000 atm were found to be constant and reproducible with an accuracy of 0.02°C.

CALIBRATION OF THERMISTORS

The resistance of each thermistor tested was found to be almost but not exactly a linear function of ambient temperature. The resistance (and consequently the thermometric behavior) of the thermistors is also influenced by pressure. It was necessary, therefore, to calibrate each thermistor for the temperature and pressure at which it was to be employed. First, it was calibrated at the ambient temperature at which it was to be employed at atmospheric pressure. This was done by adjusting the Wheatstone bridge resistances to provide for temperatures being recorded directly and correctly 5°C below to 5°C above each ambient temperature at which measurements were made. Within any 10° range between 0° and 60°C, the resistance of the 14-B thermistors was found to be directly proportional to temperature to the nearest 0.02°C.

At constant temperature (which is very difficult to realize experimentally at increasing pressures) the resistance of bead-type thermistors is influenced by hydrostatic pressure. This is illustrated by data from a representative run recorded in Table 1; compressing the system to 1000 atm starting at an ambient temperature of 25°C resulted in the thermistor's registering an apparent temperature of 28.81°C. Part of this increase was from heat of compression, but part is a reflection of the effect of pressure on the resistance of the thermistor, because when equilibrium conditions were established after half an hour by the dissipation of heat of compression in the water bath at 25°C, the

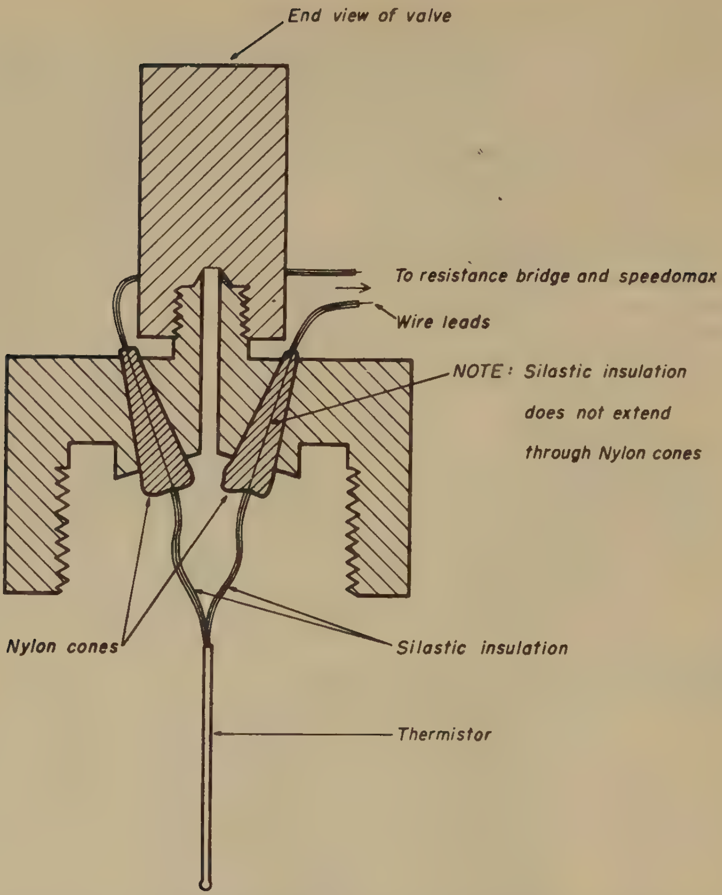
End view of valve
To resistance bridge and speedomax
Wire leads
NOTE: Silastic insulation
does not extend
through Nylon cones
Nylon cones
Silastic insulation
Thermistor

FIG. 3. Pressure vessel cap fitted with a thermistor. The current-conducting wires are insulated with a thick layer of Dow-Corning Co. "silastic." Nylon cones provide both insulation and a pressure-tight seal for the holes through which the wires pass.

thermistor registered 25.81°. In this case, the 0.81 increment represents the effect of pressure on the resistance of the thermistor. This is substantiated by the decompression of the system (see columns 7, 8, and 9 in Table 1). Immediately following decompression of the system to atmospheric pressure, it was cooled to an apparent (and actual) temperature of 21.99°C, or 3.01°C below ambient water bath temperature. Within half an hour the system was warmed by absorption of heat from the water bath until it reached equilibrium at 25.00°C. Repeating the operations any number of times yielded identical results within the limits of accuracy of the thermistor and the constancy of the water bath. When operating at 25 to 55°C, the water bath temperature remained constant to ± 0.02°, but it fluctuated by as much as 0.05° at 5°C.

The effect of compression on the resistance of thermistors in terms of °C is the compression correction factor which must be substracted from the apparent temperature registered by the thermistor at increased hydrostatic pressure to give the actual temperature. Table 2 shows these factors at ambient temperaturs ranging from 5 to 55°C at pressures from 100 to 1000 atm. For the 14-B bead-type thermistors, these

TABLE 1. *Apparent and corrected or actual temperatures recorded by 14-B bead-type thermistor in water-filled pressure vessel upon compression to 1000 atm for two hours followed by decompression in constant temperature bath at 25°C*

Time in minutes	Pressure in atm	Thermistor readings	Apparent Δt in °C	Corrected Δt in °C	Time in minutes	Pressure in atm	Thermistor readings	Corrected Δt in °C
0	1	25.00	0.00	0.00	120	1000	25.81	0.00
1	1000	28.81	3.81	3.00	121	1	21.99	3.01
2	1000	27.89	2.89	2.03	122	1	22.89	2.11
3	1000	27.40	2.40	1.59	123	1	23.45	1.55
4	1000	27.18	2.18	1.37	124	1	23.63	1.37
6	1000	26.81	1.81	1.01	126	1	23.97	1.03
8	1000	26.55	1.55	0.74	128	1	24.26	0.74
10	1000	26.35	1.35	0.54	130	1	24.45	0.55
15	1000	26.07	1.07	0.26	135	1	24.74	0.26
20	1000	25.93	0.93	0.12	140	1	24.88	0.12
25	1000	25.85	0.85	0.04	145	1	24.96	0.04
30	1000	25.81	0.81	0.00	150	1	25.00	0.00
60	1000	25.81	0.81	0.00	160	1	25.00	0.00
120	1000	25.81	0.81	0.00	240	1	25.00	0.00

In this series the compression correction factor is 0.81.

TABLE 2. *Compression correction factors for 14-B bead-type thermistor at different ambient temperatures and pressures*

Pressure in atm	Ambient temperature ± 0.05°C						
	5°	15°	25°	35°	45°	55°	Average
100	0.09	0.08	0.08	0.10	0.09	0.10	0.09
200	0.17	0.18	0.20	0.19	0.19	0.19	0.19
300	0.29	0.30	0.31	0.32	0.31	0.32	0.31
400	0.39	0.42	0.40	0.39	0.40	0.40	0.40
500	0.50	0.50	0.48	0.49	0.51	0.48	0.49
600	0.56	0.57	0.58	0.60	0.59	0.59	0.58
800	0.69	0.70	0.75	0.75	0.73	0.78	0.73
1000	0.86	0.85	0.83	0.86	0.88	0.91	0.86

factors approximate 0.1°C per 100 atm. This is somewhat more than the compression correction factors which Tavernier and Prache (1952) found for flat disc-type thermistors. Although the correction factors vary slightly with each thermistor unit, the factor appears to be independent of ambient temperature within the range of 5 to 55°C.

Owing to thermal and electrical conductivity changes induced in the element, the thermal time constant of 14-B thermistors in water was found to range from 20 to 30 seconds at 1000 atm as compared with approximately 1 second at 1 atm. The "thermal time constant" is the time required for the temperature of the element after being heated to change 63% of the difference between its initial temperature and that of its surroundings.

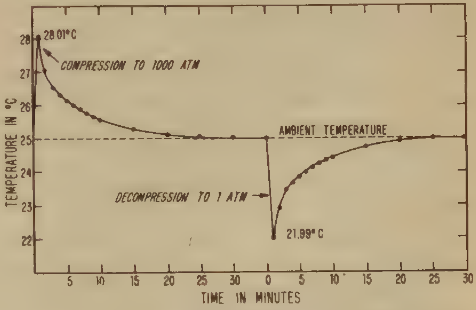

FIG. 4. Temperature changes occuring in gas-free water in steel vessel in constant temperature bath at 25°C when (1) compressed to 1000 atm within one minute, (2) held at 1000 atm for 30 minutes, (3) decompressed, and (4) held at atmospheric pressure for 30 minutes.

EXPERIMENTAL RESULTS

Filled to capacity with water, nutrient medium mineral salts solutions, or other aqueous biological materials, the closed pressure vessel, fitted with a calibrated thermistor, was submerged in a 60-gallon water bath at stated constant temperature. With the application of pressure there was an instantaneous increase in temperature (Fig. 4), from 30 to 60 seconds being required to compress the system to 1000 atm and to close the check valves. The temperature then commenced to fall as the heat of compression was dissipated in the water bath. Within 20 to

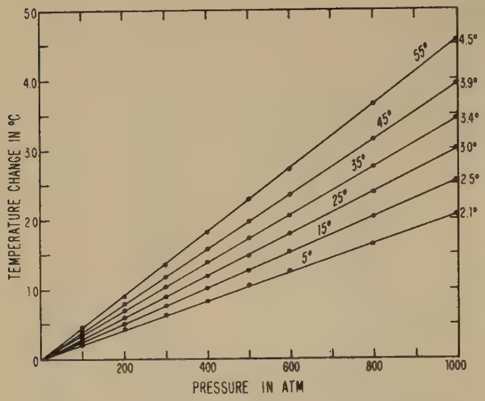

FIG. 5. Maximum temperature changes resulting from compression of gas-free water in steel vessels at ambient temperatures ranging from 5 to 55°C.

30 minutes, depending upon the pressure and consequent warming, the temperature of the compressed system returned to ambient. When equilibrium was established, the valves were opened permitting the pressure of the system to return to atmospheric. This resulted in instantaneous cooling (Fig. 4), after which another 20 to 30 minutes was required for the system to warm back to ambient.

Although not an actual measure of adiabatic heating or cooling, the procedures outlined above give a good approximation of the temperature changes which occur during the compression and decompression of experimental materials. Figure 5 shows the magnitude of the changes in gas-free water at ambient temperatures between 5 and 55°C at pressures up to 1000 atm. Within these extremes and the limits of experimental error, excluding anomalies in the behavior of heterologous systems, heat of compression increases with ambient temperature as almost a linear function of pressure.

At concentrations ordinarily found in aqueous biological materials (nutrient media, physiological salt solutions, etc.), dissolved substances have relatively little influence on the heat of compression. Higher concentrations of solutes, however, affect the heat of compression to the extent that the solutes affect compressibility and thermogenic reactions of system components. Among the many properties of liquids and solids affected by pressure are chemical reactivity, solubility, thermal conductivity, specific heat, and volume. Gases are responsible for pronounced effects of pressure; in the foregoing experiments gases were carefully excluded. The heat of compression of a 50 per cent solution of glycerol in water, employed as hydraulic fluid in the experiments, has approximately double the heat of compression of pure water. Thus the introduction of this hydraulic fluid into the pressure vessel results in anomalously high heat of compression values. Other small anomalies result from friction between the glass envelope and metallic oxides encased in the thermistor, unequal expansion or contraction in parts of the steel pressure vessel, and other mechanical effects of pressure on heterologous components, including glass culture tubes, rubber stoppers, etc.

More important than the chemical composition of the aqueous system in determining maximum heating during compression of experimental materials is the rate of compression or decompression. This will be apparent from the cooling and heating curves in Figure 4. In such experiments maximum heating occurs when pressure is applied rapidly, allowing little time for heat to be dissipated in the vessel itself and in the water bath. Gradually increasing the pressure to 1000 atm during a period of 30 minutes rather than in 30 seconds, for example, results in only negligible temperature changes. Applying pressure at the rate of heat dissipation is not always a practical means of controlling the temperature, however, because in certain experiments the biologist is concerned with reaction rates during the first few minutes of compression. In experiments such as those of Johnson (1948) on the effects of pressure on bioluminescence reaction rates or those of Johnson and ZoBell (1949) on the effects of pressure on the thermal disinfection of spores, for example, small (diameter 9⁄16 in.) pressure vessels were employed to provide for the rapid dissipation of heat of compression.

While the rapid compression of biological materials may result in temperature increases of a few degrees (Fig. 5), the increases are of short duration when the pressure vessel is submerged in a constant temperature water bath. The thermal time constant T-63 of aqueous solutions compressed in the steel pressure vessel is usually only two or three minutes; sometimes less than one minute. The rate of heat dissipation is influenced by ambient temperature, circulation of water in the bath, and by the heat capacity of the system.

DISCUSSION

Since it is difficult to predict or to duplicate all of the conditions affecting thermal changes in biological materials during compression or decompression, the magnitude and duration of such changes should be measured in experiments in which temperature may be critical in the intrepretation of results. Compressing physiological saline, common nutrient media, and similar aqueous solutions at 5 to 55°C to deep-sea pressures results in temperature increases ranging from 2 to 5°C. Decompression to atmospheric pressure results in equal cooling.

The magnitude of the thermal changes is influenced by the magnitude of the pressure change, ambient temperature, chemical composition of the system, and by other factors. Size, shape, and composition of the pressure vessel, its surroundings (temperature of air, water, etc.), and the rate of compression or decompression become significant factors to the extent that such experimental conditions affect the transfer or dissipation of heat. The rate at which heat is dissipated affects not only the magnitude of the thermal changes but also their duration in experimental materials. The thermal time constant T-63 in steel pressure vessels commonly employed for studying the effects of pressure on microbial activities ordinarily is only two or three minutes. Although the thermal changes and their duration may seem small, they have proved to be of critical importance in some of our work with thermolabile enzymes at deep-sea pressures to be reported in a subsequent paper.

REFERENCES

Becker, T. J., C. B. Green, and G. L. Pearson. 1947. Properties and uses of thermistors—thermally sensitive resistors. Elect. Engineering, **65**: 711–725.

Bjerknes, V. L., and J. W. Sandström. 1910. Dynamic meteorology and hydrography. Part I. Statics. Publ. Carnegie Inst., No. **88**: 3–146.

Bridgman, P. W. 1931. The volume of eighteen liquids as a function of pressure and temperature. Proc. Amer. Acad. Arts Sci., **66**: 184–233.

Carruthers, J. N., and A. L. Lawford. 1952. The deepest oceanic sounding. Nature, **169**: 601–603.

Dorsey, N. E. 1940. Properties of ordinary water-substance. Reinhold Pub. Corp., New York. 673 pp.

Hamann, S. D. 1957. Physico-chemical effects of pressure. Academic Press Inc., New York. 246 pp.

Johnson, F. H. 1948. Bioluminescence: A reaction rate tool. Scient. Month., **67**: 225–235.

Johnson, F. H., and C. E. ZoBell. 1949. The retardation of thermal disinfection of *Bacillus subtilis* spores by hydrostatic pressure. J. Bact., **57**: 353–358.

Kitching, J. A. 1957. Effects of high hydrostatic pressures on the activity of flagellates and ciliates. J. Exp. Biol, **34**: 494–510.

Laurson, P. G., and W. J. Cox. 1954. Mechanics of materials. John Wiley & Sons, New York. 414 pp.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming. 1942. The oceans. Prentice-Hall, Inc., New York. 1087 pp.

Tammann, G., and A. Elbrächter. 1931. Adiabatische Dilatationen an Wasser und viskosen Flüssigkeiten. Z. Anorg. Allgem. Chem., **200**: 153–167.

Tavernier, P., and P. Prache. 1952. Influence de la pression sur la résitivité d'une thermistance. J. Phys. Rad., **13**: 424–426.

Wüst, G. 1951. Die grössten Tiefen des Weltmeeres in kritischer Betrachtung. Die Erde, **4**: 203–214.

ZoBell, C. E. 1954. Some effects of high hydrostatic pressure on apparatus observed on the Danish Deep-Sea Expedition. Deep-Sea Res., **2**: 24–32.

ZoBell, C. E., and F. H. Johnson. 1949. The influence of hydrostatic pressure on the growth and viability of terrestrial and marine bacteria. J. Bact., **57**: 179–189.

ZoBell, C. E., and C. H. Oppenheimer. 1950. Some effects of hydrostatic pressure on the multiplication and morphology of marine bacteria. J. Bact., **60**: 771–781.

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INTRODUCTION TO MARINE MICROBIOLOGY

by

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7

INTRODUCTION TO MARINE MICROBIOLOGY*

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Bacteria, yeasts, fungi, microflagellates, blue-green algae, and allied microbes are widely distributed in the sea, where they have far-reaching effects on biological and geochemical conditions. The marine microbiologist is concerned with the occurrence, characteristics, and activities of such microbes in the sea. Besides being concerned with the deep sea and open ocean, he must also be cognisant of conditions of microbial life in the littoral zone, estuaries, inflowing rivers, and related lakes. Thus the domain of the marine microbiologist encompasses more than two-thirds of the earth's surface and 99 per cent of the hydrosphere.

The numbers and kinds of microbes occurring in the marine world are influenced by environmental conditions and the presence of higher organisms. A good many environmental conditions, in turn, and the well-being of many marine plants and animals are affected by the presence and biochemical activities of microbes. Obtaining quantitative information on these matters has required the development of new methods and techniques and world-wide surveys. Although bacteria have been recognised as regular components of the marine biota for nearly a century, the science of marine microbiology is still in its infancy, having received only relatively little attention. To illustrate – at the 1953 International Congress for Microbiology in Rome at which Marine Microbiology was accorded sectional status for the first time, less than 30 of the more than 5,000 registrants indicated an active interest in the sea.

EXTENT AND PROPERTIES OF THE MARINE ENVIRONMENT

Nearly 72 per cent of the earth's surface is covered with water (Sverdrup *et al.*, 1942). The area is approximately 143,000,000 square miles or about $3{\cdot}7 \times 10^{14}$ m^2. The average depth of the sea is approximately 3,800 m or about 12,000 ft. Several oceanic deeps exceeding 30,000 ft have been sounded. The greatest known depth is the Challenger Deep, 35,500 ft, in the Mariana Trench (Wüst, 1950). The total volume of the oceans of the world is estimated to be about 328,000,000 cubic miles or 14×10^{23} ml.

Exclusive of insects, few of which are marine, four-fifths of all known animal species live in the sea. Virtually all major animal phyla are represented by marine species, and part of the phyla are exclusively marine. The plant kingdom is represented by more than 8,000 species – mostly phytoplankton, although several hundred species of seaweeds and other sedentary plants are known. The known species of marine bacteria, yeasts, microflagellates, and mould fungi are numbered in hundreds only.

The depth at which photosynthetic organisms occur is limited primarily by the penetration of sunlight, a matter of 500 ft at the most. The vertical distribution of non-photosynthetic microbes and animals appears to be limited partly by the availability of food (produced primarily in the photosynthetic zone) and partly by hydrostatic pressure. The pressure-depth gradient in the sea is nearly a straight line function, pressure increasing with depth by approximately 0·1 atm/m or about 0·5 psi/ft.

Water temperatures range from −2° to 40° c. Surface water temperatures in the tropics reach 28° to 30° c or occasionally 40° c in localised areas of the littoral zone. In Arctic and Antarctic areas surface water temperatures may be as low as −2° c, the temperature at which sea water of high salinity freezes to form ice. Approximately one-half of the ocean's surface ranges from 15° to 30° c and one-fourth is colder than 10° c. Temperatures lower than 10° c characterise most water masses below the topmost strata affected by radiant energy from the sun. More than 90 per cent of the marine environment is colder than 5° c.

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The freezing point and osmotic pressure of sea water are functions of its salinity, which is generally within the range 3·2 to 3·6 per cent. Lower salinities may occur in localised areas at the surface or near-shore where sea water may be diluted by rainfall, inflowing rivers, or melting ice. The salinity may be higher than 3·6 per cent in regions of rapid evaporation, as in tide pools, marine salterns, or in isolated basins such as the Dead Sea or Great Salt Lake, in which the salinity may exceed 25 per cent.

Sodium chloride makes up about 86 per cent of the dissolved solids in sea water. Magnesium sulphate is next in order of abundance, with much smaller quantities of calcium, potassium, strontium, bicarbonate, bromide, fluoride, and borate ions. More than 60 chemical elements have been detected in sea water and virtually all are believed to be present. The organic carbon content of sea water averages 5 mg/l. The total fixed nitrogen content, including organic nitrogen compounds, nitrate, nitrite, and ammonium, is generally less than 1 mg/l. The combined nitrogen as well as the organic carbon and dissolved oxygen content of sea water is influenced by the activities of bacteria and other microbes.

CHARACTERISTICS OF MARINE BACTERIA

Morphologically, marine bacteria, as well as yeasts, mould fungi, microflagellates, blue-green algae, and other marine microbes, are much like their better known terrestrial or freshwater counterparts. While undoubtedly most of the microbes found in the sea are specifically indigenous to the marine environment, many mechanisms make for an interchange of microbes between land and the sea. Some may become airborne (ZoBell, 1942) and others may be transported by birds or other animals. Countless numbers of bacteria from soil or sewage may be carried by rivers, sewage outfalls, or other terrestrial drainage into the sea where some may survive in brackish water or become acclimatised to water of higher and higher salinity.

The majority of the bacteria collected from the sea at places remote from possibilities of terrigenous contamination require sea water or its equivalent for optimal activity. Upon initial isolation such bacteria grow poorly or not at all in nutrient media having a salinity of less than 50 per cent that of normal sea water. Although sometimes characterised as halophilic, most marine bacteria tolerate solutions hypertonic to sea water no better than they tolerate hypotonicity. This is illustrated in table 1, which summarises comparative plate counts obtained from a large number of samples from various sources used to inoculate nutrient agar prepared with balanced mineral solutions of different salinities.

TABLE 1. Average Growth Index, Expressed as Per Cent, of Bacteria From Different Sources Which Formed Colonies in Nutrient Agar Having Different Salinities

Source of Bacteria	Salinity of Nutrient Agar (%)						
	0·5	1·0	2·0	3·5	7·0	10·0	25·0
Sea water	19·2	39·0	86·9	100·0	37·2	13·8	0·2
Marine mud	24·1	35·4	78·7	100·0	44·5	9·4	0·3
Marine saltern	4·8	7·1	10·3	18·8	51·2	60·3	100·0
Great Salt Lake	2·2	5·8	13·0	25·3	38·6	68·2	100·0
Garden soil	100·0	79·1	61·7	24·4	10·9	5·3	0·4
Sewage	100·0	69·2	43·5	13·8	6·7	2·8	0·0

In view of the coldness of the marine environment (mostly less than 5° c), one might expect a psychrophilic microflora to predominate. While the majority of the bacteria taken from the sea do grow slowly at refrigeration temperatures (0° to 5° c), we have yet to find an obligate psychrophile or one which will grow better at refrigeration temperatures or even at 12° to 15° c than at 18° to 20° c. This seems somewhat anomalous since the cultures come from habitats where low temperatures prevail. Even more anomalous is the occurrence of obligate thermophiles in deep ocean basins (Bartholomew and Rittenberg, 1949) and in Arctic ice (McBee and McBee, 1956). These thermophiles are probably passive mutants which, being unable to reproduce in the cold climate where formed and found, are preserved by the low temperature. Actually marine thermophiles are so rare that they are to be regarded as biological curiosities.

The maximum temperature tolerated by most marine bacteria is only a few degrees higher than the temperature at which they grow best. Some marine bacteria which grow readily at 20° to 22° c are killed in ten minutes at 25° c. The thermal death point of marine bacteria is, in general, much lower than for bacteria from soil or freshwater sources (see table 2). Many of the bacteria occurring in sea water or marine mud are killed by short exposure to the plating temperature of nutrient agar, i.e., 42° to 45° c.

TABLE 2. Effect of Temperature on Bacteria From Various Sources, Cultured on Nutrient Agar

All plates were inoculated with properly diluted samples, and were incubated at 20° c after heating for 10 minutes to the stated temperature.

The colony counts are expressed as percentages of the counts from samples heated to 20° c.

Sample or Inoculum	Colony Counts						
	Temperature to Which Sample was Heated						
	20° c	30° c	40° c	50° c	60° c	80° c	100° c
Sea water	100	81·3	21·9	6·8	3·0	0·2	0
Marine mud	100	68·5	18·3	10·3	5·2	0·7	0
Garden soil	100	87·8	74·2	62·4	21·0	8·6	0·3
Sewage	100	84·6	70·6	57·9	9·6	1·2	0·1

TABLE 3. Relative Numbers of Marine Bacteria Appearing on Nutrient Agar at Different Incubation Periods and Temperatures

The colony counts are expressed as percentages of the average counts after 18 days at 18° c.

Period of Incubation	Temperature of Incubation						
	4–5° c	10–12° c	17–18° c	21–22° c	25–26° c	30–31° c	37–38° c
2 days	0	18	30	36	41	44	8
4 days	0	28	41	60	65	61	12
7 days	4	46	67	82	78	69	12
10 days	9	67	91	96	84	71	13
14 days	17	90	98	97	85	70	10*
18 days	26	97	100	95	82	63	8
21 days	33	98	96	87	74	53	7
28 days	69	104	91	75	69	42	4
35 days	99	98	87	69	58	31	4

*Decrease in counts due to merging of colonies and desiccation of medium.

Colony counts are nearly always higher on plates of nutrient agar incubated at 18° to 22° c than at higher temperatures (ZoBell and Conn, 1940). As many colonies of marine bacteria may develop on nutrient agar at 5° or 10° c as at 20° c, but much longer periods of incubation are required for the formation of visible colonies at the lower temperatures (see table 3).

Bacteria taken from sea water or sediments at depths of less than 1,000 m are affected by hydrostatic pressure in much the same way as are common soil, sewage, and freshwater bacteria (ZoBell and Oppenheimer, 1950). Their growth is inhibited when cultures are compressed to 200 to 400 atm at optimum temperature and they slowly die off when held for a few days at pressures ranging from 300 to 600 atm (Oppenheimer and ZoBell, 1952). On the other hand, most of the bacteria taken from depths of 7,000 to 10,000 m grow only when incubated at pressures characteristic of their natural habitat, i.e., 700 to 1,000 atm (ZoBell and Morita, 1957a, b).

OCCURRENCE OF BACTERIA IN THE SEA

Throughout the photosynthetic zone the abundance of bacteria appears to be more closely related to the distribution of phytoplankton than to any other single ecological factor (Waksman *et al.*, 1933). The beneficial effect of plankton is attributed partly to the organic matter which they provide and partly to solid surfaces. Bacteria occur only to a limited extent free-floating in water; most of them are attached to suspended solids such as the bodies or remains of plankton organisms. As pointed out by ZoBell (1943), solid surfaces tend to concentrate organic nutrients, retard the diffusion of exoenzymes away from bacteria, and provide a resting place for sessile forms. Waksman and Vartiovaara (1938) found most of the bacteria in marine bottom deposits adsorbed on or attached to particles of sediment.

In the open ocean the abundance of bacteria generally increases with depth from the surface down to a depth of 25 or 50 m, below which they decrease in numbers. Below 200 m living phytoplankton are only rarely encountered and the bacterial population is usually less than 10 per ml until the bottom is reached. Sea water is almost sterile in many parts of the ocean at depths below 1,000 m. Kriss (1952) obtained no growth in nutrient broth inoculated with 35 ml samples in 29·6 per cent of 270 deep-water samples from 50 stations in the Okhotsk Sea and northern Pacific Ocean.

At the mud-water interface, the zone of maximum bacterial activity, the bacterial population ranges from 10^2 to 10^7 per ml as compared with average counts of 10^2 to 10^4 per ml in the photosynthetic zone. Only in bottom sediments or in localised areas does the density of bacteria often exceed 10^4 per ml. Assuming an average bacterial population of 10 per ml in water throughout the oceans of the world, the standing crop of bacterial biomass would amount to about 10^6 tons. If these bacteria reproduce at an average rate of only once per day, a rate believed to be conservatively slow, the annual yield of bacterial biomass in the ocean would amount to $3{\cdot}65 \times 10^8$ tons. The total primary productivity of sea has been estimated by various workers to range from 5×10^{10} to 9×10^{11} tons per year.

The storage of sea water in clean glass receptacles is usually accompanied by a fairly rapid increase in its bacterial population. Under storage conditions the bacteria may reproduce every hour or two. Their reproduction in stored water samples raises the question as to why there are so few bacteria in sea water, which is capable of supporting many more. Bacterial predators, which do not survive long under ordinary storage conditions, may help to keep counts low in the sea. The favourable effects of solid surfaces provided in storage conditions are believed to be chiefly responsible for the increased bacterial populations.

In sediments on the sea floor, where both solid surfaces and organic matter are usually more abundant than in overlying water, the bacterial population compares favourably in the diversity of species and in total numbers with fertile garden soil. Both the abundance and number of bacterial species decrease with core depth, the maxima occurring in the topmost few millimetres of mud. Within the topmost metre of mud the bacterial population generally falls off from 10^2 to 10^7 to less than 10 per ml. Viable bacteria, however, have been detected at the bottom of some of the longest cores examined, nearly 10 m, consisting of sediments as old as 10^5 years.

Most of the bacteria recovered from marine bottom deposits prove to be facultative or strict anaerobes. Bacteria are sparse in red clays and other pelagic sediments which are poor in organic matter (Morita and ZoBell, 1955). According to Kriss and Rukina (1952), Okhotsk Sea and northern Pacific Ocean sediments contain 10^8 bacteria per gram to give a bacterial biomass estimated to range from 0·2 to 1·4 g/m². If comparable bacterial densities occur in all ocean sediments, the standing crop of bacterial biomass would range from 7×10^7 to 5×10^8 tons.

Large numbers and many different species of bacteria are found associated with the integuments and digestive tracts of marine animals. Seaweeds – both living and dead – support the growth of an extensive microflora, including bacteria as well as mould fungi and yeasts.

OTHER MARINE MICROBES

Yeasts are only occasionally encountered in the sea except in association with seaweeds. Several varieties of *Torula, Mycoderma, Blastoderma, Oidium, Dematium, Endomyces,* and *Saccharomyces* have been isolated from marine materials. Yeasts are an important component of the microflora in the Black Sea where Kriss and Rukina (1952) found them associated with seaweeds, in superficial layers of water, and in deeper water masses.

Although mould spores and mycelium fragments are commonly detected in sea water throughout the photosynthetic zone and on the sea floor at the mud-water interface, the growth of fungi in the sea seems to be confined primarily to diseased or decomposing plant and animal tissues. Several genera of marine Fungi Imperfecti, Phycomycetes, and Myxomycetes have been described, mostly from near-shore materials. Among the many species of marine fungi described by Sparrow (1936) is an *Ectrogella* that infects certain diatoms. Seaweeds seem to be very susceptible to invasion by both saprophytic and parasitic fungi. Widespread mortality in oysters has been traced to a fungus disease caused by *Dermocystidium marinum* (Andrews and Hewatt, 1957).

Important constituents of nannoplankton or ultraplankton that escape most conventional plankton nets are the so-called microflagellates or naked flagellates which are mostly less than 5 microns in diameter. These inadequately investigated microbes are believed to contribute substantially to food cycles in the sea (Butcher, 1952; Knight-Jones and Walne, 1951).

Only a few varieties of filterable viruses have been reported in the sea, probably because these minute microbes have received only desultory attention. Certain marine aquarium fish have been shown to be infected by viruses and a few marine bacteriophages have been reported. A disease of the giant kelp, *Macrocystis pyrifera,* resembles virus infections of certain spermatophytes, but conclusive evidence for a virus infection of this or any other alga is still lacking. Marine diatoms and dinoflagellates appear to suffer from infections, but whether filterable viruses or other microbes are involved has not been determined.

Marine microbiology may include studies of diatoms, dinoflagellates, silicoflagellates, coccolithophores, ciliates, radiolaria, foraminifera, and other small organisms along with viruses, bacteria, yeasts, mould fungi, microflagellates, and blue-green algae. All are of great geological and biological significance in the sea and they have many properties in common. The former larger organisms are not treated here nor in my book entitled "Marine Microbiology" (1946a), because I believe the major domain of the marine microbiologist is the community of microbes that, owing to their size and behaviour, are studied primarily by cultural methods or with a microscope at a magnification of about 1,000 times.

HARMFUL EFFECTS OF MARINE MICROBES

Although their activities are preponderantly beneficial, there are ways in which marine microbes are deleterious to the economy of the sea or to the welfare of man. Their most obvious harmful effect is in causing infectious diseases of marine plants or animals. Salmon, lobsters, oysters, and numerous fish kept in marine aquaria are among the animals known to be adversely affected by marine microbes (ZoBell, 1946a). The wasting disease of eel grass, *Zostera marina.* is an outstanding example of a devasting microbial infection of marine plants (Renn, 1936). The sea, however, is inhospitable to most human pathogens. Organisms such as typhoid bacilli and cholera vibrio survive in the sea for only a few days. They may survive in waters or on beaches polluted with sewage long enough to be potentially dangerous to man. Likewise they may be transmitted to man in oysters or other contaminated shellfish.

Fish and certain other marine foods are extremely susceptible to bacterial spoilage. Considerable attention has been devoted to the enumeration, identification, and control of bacteria associated with fish, a subject which would require an extensive monograph to bring the voluminous literature together. Applications of the principles of modern sanitation, refrigeration, and chemical preservatives, including nitrite and antibiotics, have helped to lessen spoilage (Tarr, 1954). The spoilage of fish is caused primarily by bacteria that live in the digestive tracts or in the slime of the fish. Species of *Achromobacter, Pseudomonas, Flavobacterium,* and *Micrococcus* predominate in the spoilage of marine fish. These genera also predominate in the sea. Species of *Sarcina, Proteus,* and *Bacillus* occur less frequently. Many of the fish-spoilage bacteria are pigmented and may cause objectionable discolouration in refrigerated fish. Rapidly cooling the fish as soon as they are caught and holding them at near 0° C will substantially lessen undesirable changes caused by bacteria, but temperatures lower than $-7{\cdot}5°$ C are required to stop the activity of facultative psychrophilic bacteria associated with marine fish.

Cellulose decomposers and other physiological groups of bacteria participate in the rapid rotting of wooden pilings, board boat bottoms, cordage, fish nets, lines, and ropes in the marine environment. Bacteria are also involved in the biofouling of ships' bottoms, water conduits, and other submerged surfaces. By producing acids in microspheres as well as by other mechanisms bacteria promote the corrosion or deterioration of man-made iron, steel, and concrete structures in the sea.

In localised areas, as in bays or stagnant basins, bacteria may vitiate water by depleting dissolved oxygen, by producing hydrogen sulphide, or by forming toxic amines. Taken as a whole, the marine bacteria probably consume more oxygen than all other marine organisms combined. When oxygen is consumed more rapidly than it can be replaced by solution from the atmosphere or by photosynthetic processes, conditions tend to become anaerobic and hydrogen sulphide may accumulate. Hydrogen sulphide is produced both by the anaerobic decomposition of proteinaceous compounds and the reduction of sulphate. In places like the Black Sea or stagnant fjords, bacteria may produce hydrogen sulphide in concentrations high enough to be incompatible with other forms of life. The catastrophic death of animals in the wake of "red tide" is believed to be partly attributable to the vitiation of water massses by bacteria.

Red tide is the name applied to waters discoloured by aggregations of algae, bacteria, ciliates, diatoms, flagellates, and other pigmented organisms. Extensive areas of water assume a red, brown, amber, or greenish-yellow hue. The dinoflagellates *Goniaulax monilata, Gymnodinium brevis,* and *Ceratium furca* and the bacterium *Flavobacterium piscicida* are among the many microbes associated with catastrophic mass mortality of fish and other marine organisms.

It was once thought (Brandt's hypothesis, 1929) that the denitrifying bacteria which liberate free nitrogen from nitrate limit the amount of nitrate available for the growth of phytoplankton in tropical seas. The activities of denitrifiers, which are known to be abundant in the sea, are unquestionably responsible for a leak in the nitrogen cycle. This effect is limited largely by a lack of organic matter which the denitrifiers require as an energy source.

MICROBIAL MODIFICATION OF ORGANIC MATTER

The most important activity of bacteria in the sea is the mineralisation or modification of organic matter (Waksman, 1934). In places this may be harmful to the economic interests of man or to the general economy of the sea, but it is mostly beneficial. It results in the formation of plant nutrients, notably ammonium and phosphate, and in the decomposition of the remains of plants and animals. Dissolved, colloidal, or waste organic matter unfit as food for other organisms may be transformed by bacteria into cell substance utilisable as nutritious food for animals.

Virtually all classes of organic compounds – carbohydrates, lipids, proteins, hydrocarbons – are attacked and almost quantitatively assimilated by bacteria. Except in localised areas the concentration of organic carbon in sea water is reduced to less than 5 mg/l. Most marine bottom deposits contain less than 5 per cent organic matter, the content decreasing with core depth, age, or the time that bacteria have had to act. Concentrations of organic carbon higher than 5 mg/l generally provide for the rapid reproduction of heterotrophic bacteria which oxidise organic compounds. Owing to the speed with which organic compounds are modified, the sea has been called the world's largest and most efficient septic tank.

Under aerobic conditions, the principal decomposition products resulting from the bacterial oxidation of organic compounds are water, carbon dioxide, sulphate, ammonium, and phosphate. The last two are plant nutrients which may limit primary productivity in the sea. Ammonium may be utilised directly by plants or it may be oxidised by bacteria to nitrite or nitrate. Carbon

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dioxide, water, ammonium, phosphate, methane, molecular hydrogen, and hydrogen sulphide are liberated when organic matter is attacked under anaerobic conditions. Complex organic compounds are converted, in part, to marine humus (Waksman, 1933). Humus also consists partly of complex organic compounds making up bacterial cell substance.

From 10 to 40 per cent or more of the carbon content of organic compounds utilised by heterotrophic bacteria may be converted into bacterial protoplasm. Being nutritious and usually readily digestible, such bacterial cell substance constitutes an important part of the diet of many marine animals. Bacterial species that live normally in the gut of animals may aid them in the digestion of food. Bacterial enzymes catalyse the hydrolysis of cellulose, chitin, alginates, agar, hydrocarbons, and other complex organic compounds. Bacteria also produce vitamins essential in the nutrition of animals.

Chitin is a complex glucosamine occurring commonly in Mollusca, Coelenterata, Protozoa, fungi, and Crustacea in which it is the chief exoskeleton constituent. From data on the abundance of copepods and their chitin content it is estimated that just this one sub-class of Crustacea produces several million tons of chitin annually in the oceans of the world. Bacteria are believed to be the principal agents responsible for the decomposition or digestion of chitin. Hock (1940) isolated chitinoclastic bacteria from marine sediments, sea water, decomposing crabs, and from the intestinal contents of several animals which ingest copepods or other organisms containing chitin.

Agar, which normally occurs in a large variety of seaweeds, is a complex galactan which is digested by bacteria. Nearly fifty species of marine agar digesters have been described by Humm (1946). He detected from 2 to 150 agar digesters per ml of sea water and from 80,000 to 20,000,000 per gram of mud along the coast of North Carolina. All of Humm's agar digesters utilised cellobiose, 85 per cent attacked salicin, 70 per cent attacked alginic acid, 25 per cent attacked chitin, and 20 per cent attacked cellulose.

Cellulose-decomposing bacteria are generally present in sea water, being most plentiful in plankton tows and in bottom deposits. Most marine cellulose decomposers are aerobic. Anaerobic cellulose decomposers are only rarely detected in marine materials. The decomposition of cellulose fibre fishing nets was attributed primarily to aerobes by Kadota (1956). He studied several species of *Vibrio, Cytophaga,* and *Pseudomonas* from the sea that attacked cellulose but not cellulose acetate.

The paucity of amino acids and simple proteins in sea water and sediments is ascribable to the susceptibility of these nitrogenous compounds to microbial attack. As a class, marine bacteria are actively proteolytic; probably even more so than the microflora of garden soil or fresh water. Gelatin is liquefied so rapidly by so many marine bacteria that it is not a satisfactory substance to render nutrient media solid. Proteolytic bacteria are primarily responsible for the spoilage of fish, shellfish, crab meat, and other proteins decomposed with the liberation of ammonium, indole, trimethylamine, histamine, hydrogen sulphide, etc. (Beatty and Gibbons, 1937)

AUTOTROPHIC BACTERIA

Both chemosynthetic and photosynthetic autotrophs occur in the sea, where they contribute to the synthesis of organic matter. Photosynthetic bacteria are confined largely to shallow bottoms, brackish waters, and decomposing vegetation, where they may affect the sulphur cycle in the sea more than the carbon cycle. It has not been demonstrated whether they have any significant effect on the formation or transformation of carbon compounds. Below the photosynthetic zone chemosynthetic autotrophic bacteria appear to be the only primary producers of organic matter. Whether they produce enough to be of significance in the carbon economy of the sea is problematical. Rather widely distributed are bacteria which oxidise either hydrogen sulphide, methane, molecular hydrogen, or ammonium as an energy source while reducing carbon dioxide to build cell substance. There are no data to serve as a sound basis for estimating how much organic carbon is produced in the ocean by these autotrophs whose activities must be limited largely by the availability of hydrogen sulphide, methane, molecular hydrogen, or ammonium respectively.

Hydrogen sulphide may be precipitated from solution as metallic suphides, it may be abiogenically oxidised to other products, or it may have other fates, but the more inert methane and hydrogen, which are produced in large quantities during the anaerobic decomposition of organic matter, must be oxidised by autotrophic bacteria or escape into the atmosphere. Since methane- and hydrogen-oxidising bacteria respectively are commonly found near places where these gases are being produced, and since little or no methane or molecular hydrogen occurs in water away from such places, it is tacitly assumed that these gases are oxidised by bacteria. Ammonium may be utilised directly by plants or bacteria as a source of nitrogen, and large quantities are probably oxidised to nitrite by nitrifying bacteria. The latter may fix or convert into bacterial protoplasm 1 mg of carbon dioxide carbon for each 5 or 6 mg of ammonium oxidised. The ammonium content of sea water ranges from 0·05 to 50 mg/m^3.

NITROGEN FIXATION

Nitrogen-fixing *Azotobacter* and *Clostridium* species apparently do not occur commonly in the sea except near land. One would hardly expect to find *Rhizobium* species in the sea, since there are no marine legumes. Recent observations, however, suggest that biological nitrogen fixation is not confined to *Azotobacter, Clostridium,* and *Rhizobium* species. Certain hydrogenase-producing varieties of *Desulfovibrio,* which are widely distributed in the sea, have been shown to fix nitrogen (Sisler and ZoBell, 1951). According to Lindstrom *et al.* (1951), a good many other hydrogenase-producing bacteria, including species of *Rhodospirillum, Rhodopseudomonas,* and *Rhodomicrobium,* fix nitrogen. Pine and Barker (1954) have demonstrated nitrogen fixation by a *Methanomonas* species, and Rodina (1956) observed nitrogen fixation by a *Spirillum* species. Species of *Nostoc, Anabaena,* and certain other blue-green algae also fix nitrogen.

MICROBIAL TRANSFORMATION OF SULPHUR

From a geobiological point of view, the contribution of bacteria to the sulphur cycle in the sea is second in importance only to their essential role in the formation and transformation of carbon and nitrogen compounds. This cycle can be said to start with sulphate, of which sea water normally contains from 0·24 to 0·27 per cent. Plants as well as most bacteria can obtain the sulphur essential for the synthesis of their protoplasm from sulphate. In so doing sulphate is partly reduced and converted into organic sulphur compounds. The latter ultimately undergo decomposition, a process in which a large variety of bacteria participate.

Under anaerobic conditions sulphur is liberated from organic compounds primarily as hydrogen sulphide. Organic sulphates may be hydrolysed both aerobically and anaerobically with the liberation of sulphate. In aerobic environments hydrogen sulphide is also an important hydrolysis product of albuminous material but, depending upon the pH and Eh, an appreciable part of the hydrogen sulphide liberated in oxygenated waters may be abiogenically oxidised to elemental sulphur or sulphate. In the presence of heavy metals part of the hydrogen sulphide will be precipitated from solution. Iron and other metallic sulphides may be buried in sediments, this being one of the chief causes of their blackness, or precipitated sulphides may be dissolved and returned to the cycle as a result of certain bacterial activities which tend to lower the pH.

Sulphate-reducing bacteria of the genus *Desulfovibrio* and possible other genera liberate large quantities of hydrogen sulphide from inorganic sulphates. Hydrogen sulphide from this source may accumulate in concentrations sufficiently high to render certain environments (e.g., the deeper parts of the Black Sea, stagnant water basins, wake of the "red tide") inhospitable to other forms of life.

In the presence of light at favourable hydrogen-ion concentrations purple sulphur bacteria oxidise hydrogen sulphide to elemental sulphur or to sulphate, even in the absence of free oxygen. Likewise in the absence of free oxygen where nitrate is present *Thiobacillus denitrificans* may oxidise hydrogen sulphide, elemental sulphur, or thiosulphate. This and other species of *Thiobacillus* catalyse similar oxidations in the presence of free oxygen.

Several genera of achromic sulphur bacteria that oxidise hydrogen sulphide, elemental sulphur, sulphite, or thiosulphate occur in the sea. Their activity, like that of other bacteria which enter the sulphur cycle in the sea, is influenced by oxygen tension, Eh, pH, light penetration, interrelations with other organisms, and organic content of the water or mud (van Niel, 1936; Baas Becking and Wood, 1955). Sulphate reducers are most abundant and active in bottom deposits (ZoBell and Rittenberg, 1948). Being strict anaerobes, sulphate reducers occur in water only in localised areas. They utilise a large variety of organic compounds. Some are autotrophs which can utilise molecular hydrogen as an energy source (Sisler and ZoBell, 1950). Their common association with petroleum and sulphur deposits coupled with other evidence suggests that sulphate-reducing bacteria play a part in the origin of oil (ZoBell, 1952) and the deposition of sulphur (Jones, 1955).

PHOSPHATE REGENERATION

A lack of phosphate in certain waters is believed to limit plant productivity. Phosphate may also limit the bacterial decomposition of certain kinds of organic matter. Phosphate is depleted from waters primarily by plants and bacteria which use it in their nutrition for the synthesis of phosphoproteins and phospholipids. The phosphorus requirements of animals are satisfied by the ingestion of plants, bacteria, or other animals. Large quantities of phosphorus become bound in the bodies of organisms or their remains. Part of this sinks to the sea floor and unless placed back in solution may be removed from the phosphorus cycle by burial. In alkaline environments phosphate may be precipitated from solution and ultimately buried in sediments.

Bacteria play an indispensable role in the phosphorus cycle by decomposing organic phosphorus compounds with the regeneration of phosphate and by producing acids which tend to dissolve phosphates (Renn, 1937). There is no evidence for a biological change in state of oxidation of phosphorus, although high-energy phosphates participate in many oxidations. The solubility of phosphate in sea water is largely a function of pH, a property which is influenced by bacterial activities.

EFFECTS OF BACTERIA ON PHYSICOCHEMICAL CONDITIONS

Sea water is normally well buffered to provide a reaction ranging from pH 7·5 to 8·5. In localised environments bacterial activities may cause the pH to be extended beyond this range. The pH may be increased by the (a) formation of ammonia from the decomposition of proteinaceous substances, (b) reduction of nitrate or nitrite, (c) reductions of sulphate, (d) oxidation or decarboxylation of organic acids, and (e) assimilation of carbon dioxide. During phytoplankton blooms, photosynthetic organisms may consume carbon dioxide rapidly enough to raise the pH of surrounding water to 8·8.

The pH of water or sedimentary materials may be decreased by bacteria which (a) oxidise ammonia to nitrite or nitrate, (b) oxidise hydrogen sulphide or sulphur to sulphate, (c) produce carbon dioxide or organic acids, or (d) liberate phosphate from organic compounds. Ordinarily under natural conditions both acidifying and alkalinising processes are taking place simultaneously so there is little or no change in pH, but in localised environments, as in sediments or microspheres, one bacterial process or another may predominate. For example, certain sulphur bacteria may produce enough sulphuric acid from the oxidation of hydrogen sulphide or sulphur to depress the pH of sea water to 4·5 or lower. On the other end of the scale the bacterial reduction (destruction) of nitrate has resulted in certain media becoming more alkaline than pH 9·5.

Although one might expect sulphate reduction to result in highly alkaline conditions, sulphate-reducing bacteria generally lower the pH because, in oxidising large quantities of organic matter or hydrogen as energy sources for the reaction, they produce acidic products in excess of the effect on pH of the sulphate reduced.

For many years the study of marine microbiology was motivated by the alleged importance of denitrifying bacteria in the precipitation of calcium carbonate in shallow tropical seas. The extensive observations of Drew, Lipman, Bavendamm (1932), Baier (1937), and others have established that calcium carbonate precipitation is influenced by microbial activities; mostly by their effects on the pH, which affects the solubility of calcium carbonate.

The solubility of iron and manganese is influenced by the pH. The solubility of these minerals as well as their state of oxidation is also influenced by the redox potential. The Eh and pH of water or sediments are probably much more important in the decomposition of iron and manganese in the sea than the activities of iron- or manganese-oxidizing bacteria. Bacteria appear to be the principal dynamic agents which lower the redox potential of marine sediments. This they do by consuming free oxygen and by destroying other oxidising materials or by producing hydrogen sulphide and other reducing agents. The redox potential of sediments affects their chemical composition, reactivity, diagenesis, colour, biota, and other properties (ZoBell, 1946b; Baas Becking and Wood, 1955). Reducing conditions favour the formation and preservation of petroleum hydrocarbons.

ORIGIN OF OIL

Crude oil or petroleum, which consists largely of gaseous, liquid, and solid hydrocarbons, is believed to be formed in shallow seas where the rate of sedimentation is rapid, organic productivity is high, and conditions are reducing. In such an environment, it is the general tendency of bacteria to attack organic matter with the selective removal of oxygen, nitrogen, sulphur, and phosphorus, thereby leaving carbon complexes that are relatively richer in hydrogen or more akin to petroleum in chemical composition than the original organic matter. In so doing, bacteria often produce appreciable quantities of methane, an important constituent of crude oils and natural gas. Large quantities of molecular hydrogen are also produced during the anaerobic fermentation of organic matter. Free hydrogen, however, is rarely detected in source sediments of petroleum, probably because it is used by bacteria either to reduce sulphate or to react with carbon compounds, including carbon dioxide, to form hydrocarbons or similar compounds (ZoBell, 1952).

The original organic matter, particularly that in oil-rich diatoms, may consist in part of hydrocarbons which bacteria liberate during the decomposition of associated proteins and carbohydrates. Some of the organic matter assimilated by bacteria is converted into bacterial protoplasm consisting of from 0·02 to 0·5 per cent of liquid and solid hydrocarbons. By dissolving carbonate or sulphate rocks on which oil is absorbed or held in capillary spaces, bacteria may promote its release, flow, and accumulation in pools.

Whether crude oil could be formed in the absence of bacteria or whether bacteria play more than a minor role in the origin of oil is yet to be determined. Unquestionably, though, bacteria do influence the modification of organic matter and physicochemical conditions in source sediments of petroleum.

BIOLUMINESCENCE IN MARINE MICROBES

Luminous microorganisms are preponderantly marine. Relatively only a few terrestrial forms are known. Fish as well as the flesh of most animals, both marine and freshwater or terrestrial, may become overgrown by luminous bacteria. Parasitic luminous bacteria infect freshwater shrimps, certain insects, amphipods, and millipedes, causing these terrestrial animals to glow brightly in the dark. Luminescence in dead vegetable matter such as wood, roots, potatoes, and fruit is usually due to luminous fungi generally of the class Basidiomycetes, none of which are marine.

It is in the sea, however, that most varieties and the largest populations of luminous bacteria occur. The organic remains of virtually all kinds of marine plants and animals may support the growth of such bacteria. Only a few animal species are known to be invaded by parasitic luminous bacteria. Beach fleas, certain crabs, and shrimps appear to be particularly susceptible to such infections. A good many other marine animals may be also, but getting incontrovertible evidence is difficult. Finding dead or moribund animals aglow with luminous bacteria fails to prove the pathogenicity of the latter. Luminous bacteria commonly found associated with apparently healthy fish, squid, or other animals may be either symbiotic or purely saprophytic species.

Luminescence in certain jelly-fish, ctenophores, pennatulids, euphausids, squid, and fish has been attributed by various investigators to the activities of symbiotic luminous bacteria. Bacterial symbiosis, however, has been established in the light organs or glands of only a few species of fish and squid (Harvey, 1952; Haneda, 1955).

Most luminous bacteria are saprophytic, growing readily on a great variety of proteinaceous materials. They may grow in sufficient abundance on the dead and decomposing remains of plants and animals to create conspicuous areas of luminescence in the surf along beaches, in waves breaking over reefs, in the wake of vessels, etc. Luminous dinoflagellates, however, including species of *Goniaulax*, *Ceratium*, *Peridinium*, and *Prorocentrum*, are responsible for the most intense displays of luminescence.

Luminous bacteria from the sea require either sea water or a similar balanced mineral-salts solution containing from 1·5 to 3 per cent sodium chloride for their growth. From 3 to 4 per cent salt is required for maximum luminescence. Free oxygen is also required for luminescence. Light emission by luminous bacteria can occur at such low oxygen tensions that they have been employed to detect traces of oxygen.

METHODS IN MARINE MICROBIOLOGY

Various devices have been developed to provide for the aseptic collection of water samples from any desired depth in the sea (ZoBell, 1941). Most of these devices consist of tubes, bottles, flasks, or bulbs that can be sterilised and submerged sealed with a piece of capillary glass tubing. Provisions are made for breaking the glass tubing by a messenger-activated mechanism, thereby admitting water. Closing is not necessary to prevent contamination, because as the sample is hauled toward the surface the resultant diminishing pressure tends to force water or entrapped air slowly from the receptacle. Either tremendously sturdy receptacles or reversibly collapsible ones, like rubber or polyethylene bottles, are required to cope with high pressures encountered at great depths. Such sampling devices are usually designed to operate on a standard hydrographic wire in tandem with each other or with reversing thermometers, Nansen bottles, etc. In this way water samples or temperature data can be obtained from several different depths simultaneously by a single cast. Though useful, even the best bacteriological water samplers need improvement to make them perfect.

Samplers for collecting mud or other bottom deposits leave much to be desired. Various kinds of grabs, dredges, snappers, scoops, tubes, and corers that are used for this purpose generally provide only rather crude samples. It is rarely known with exactness the depth to which such samples penetrate bottom sediments, there may be some mixing of materials, and it is difficult to provide for aseptic operations. Despite these shortcomings bottom samples suitable for bacteriological analysis have been obtained from some of the deepest parts of the ocean. Results of quantitative significance have been obtained, because the bacterial population of bottom deposits is generally so much higher than that in the overlying water that contact with water makes little quantitative difference. Radially central sub-samples aseptically dissected from firm cores provide material for reliable results. Urgently needed are devices for obtaining micro-strata at the mud-water interface, the zone of most intense bacteriological activity in the sea. Aqualung divers can obtain such samples in manually manipulated apparatus, but they are restricted to shallow depths.

Both water and sediment samples should be analysed as soon as possible following collection. Storage for only a few hours even under the most favourable conditions of refrigeration may result in appreciable changes in the total numbers and kinds of bacteria in samples of marine materials. This usually dictates the necessity of examining samples at sea, since it may require several hours or days to transport samples to the shore laboratory. Of cardinal importance is refrigeration of the samples owing to the thermosensitivity of so many marine microbes. Fast freezing followed by refrigeration near −10° C seems to be the best way to preserve samples with a minimum of change when field conditions make it impracticable to start examinations by cultural or direct microscopic procedures. Fast freezing, though, is not without its pitfalls.

The motions of a ship at sea coupled with a lack of facilities ordinarily found in laboratories ashore necessitates many modifications of routine techniques and equipment. Provisions must be made to prevent test tubes, bottles, pipettes, etc. from tipping over, rolling, or sliding away. Such a simple operation as pouring a plate of nutrient agar on a rolling ship it attended by many difficulties: unless the agar is cooled to near 42° C before pouring and rapidly cooled below 30° C immediately after pouring, many thermosensitive bacteria may be killed. Before congealing, the agar may slop out of plates unless stabilised on a platform hung on gimbals or mounted on a gyroscope. Flat-sided, six-ounce, screw-capped bottles are preferred to Petri plates for growing bacteria in nutrient agar at sea.

So diverse are the nutrient and cultural requirements of marine microbes from different materials or places that a nutrient medium is yet to be formulated to provide for the growth of more than a small percentage of the total number present. It is necessary to employ media and conditions tailored to satisfy the requirements of each particular kind or group of microbes.

The well known limitations of direct microscopic methods are multiplied by the motion of a ship at sea. Excessive vibrations may make it impossible to keep a compound microscope in focus at the high magnifications required to recognise bacteria. Only on calm seas and when the engines are idling or stopped is it possible to make direct microscopic counts of bacteria in sediment or other marine materials. The bacterial population of most water samples is so sparse that concentration by centrifugation, filtration, or flocculation may be necessary to make direct microscopic observations meaningful. The molecular or millipore filter is proving to be a useful tool for concentrating microorganisms for direct microscopic observation or for cultivating them as colonies.

SOME UNSOLVED PROBLEMS

An accurate assessment of the importance of bacteria and allied microorganisms in the sea requires many more observations on their numbers and kinds in water masses and bottom deposits in different parts of the world. There is a crying need for improved methods for collecting and analysing samples of marine materials. World-wide cooperation is desirable to provide for the standardisation of techniques and the exchange of ideas.

Microbiologists can contribute substantially to the science of the sea, to basic biology, and to the welfare of man by giving detailed attention to the solution of problems such as the following:

Microbial fixation of nitrogen in the sea.

Microbial infections of marine plants and animals. Are marine algae invaded by viruses?

Factors affecting the survival of bacteria of sanitary significance in the sea.

Microbial growth-promoting and growth-inhibiting properties of marine materials.

Microbial modification of marine food products and control measures.

Role of bacteria and microflagellates in nutrition of marine animals.

Microbial degradation of natural debris in the sea and on beaches.

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Microbial concentration of trace elements such as vanadium, manganese, radioactive isotopes, etc.

Microbial characterisation of water masses by determining populations or using bioassay techniques.

Contributions of bacteria, microflagellates, blue-green algae, etc. to the biomass in the sea.

Phylogenetic position of microbes that are singularly affected by salinity, temperature, and/or hydrostatic pressure.

REFERENCES

Andrews, J. D.; Hewatt, W. G., 1957: Oyster Mortality Studies in Virginia. II. The Fungus Disease Caused by *Dermocystidium marinum* in Oysters in Chesapeake Bay. *Ecol. Monogr. 27*:1–26 (25 ref.)

Baas Becking, L. G. M.; Wood, E. J. F., 1955: Biological Processes in the Estuarine Environment. I. Ecology of the Sulphur Cycle. *Proc. K. ned. Akad. Wet. B58*:160–81 (20 ref.)

Baier, C. R., 1937: Die Bedeutung der Bakterien für den Kalktransport in den Gewässern. *Geol. Meere. 1*:75–105 (129 ref.)

Bartholomew, J. W.; Rittenberg, S. C., 1949: Thermophilic Bacteria from Deep Ocean Bottom Cores. *J. Bact.* 57:658.

Bavendamm, W., 1932: Die mikrobiologische Kalkfällung in der tropischen See. *Arch. Mikrobiol. 3*:205–76 (143 ref.)

Beatty, S. A.; Gibbons, N. E., 1937: The Measurement of Spoilage in Fish. *J. biol. Bd. Can. 3*:77–91 (25 ref.)

Brandt, K., 1929: Phosphate und Stickstoffverbindungen als Minimumstoffe für die Produktion im Meere. *Rapp. Cons. Explor. Mer 53*:5–35 (75 ref.)

Butcher, R. W., 1952: Contributions to Our Knowledge of the Smaller Marine Algae. *J. Mar. biol. Ass. U.K. 31*:175–91 (20 ref.)

Haneda, Y., 1955: Luminous Organisms of Japan and the Far East. In "Luminescence of Biological Systems", F. H. Johnson (Ed.). American Association for the Advancement of Science, Washington, D.C. Pp. 335–85 (211 ref.)

Harvey, E. N., 1952: "Bioluminescence". Academic Press, New York, 649 pp. (1800 ref.)

Hock, C. W., 1940: Decomposition of Chitin by Marine Bacteria, *Biol. Bull., Woods Hole, 79*:199–206 (17 ref.)

Humm, H. J., 1946: Marine Agar-digesting Bacteria of the South Atlantic Coast. *Bull. Duke Univ. Mar. Sta. 3*:45–75 (48 ref.)

Jones, G. E., 1955: Fractionation of the Stable Isotopes of Sulfur by Microorganisms with Particular Reference to the Sulfate-reducing Bacteria. *Doctorate Diss.*, Rutgers Univ., 187 pp. (147 ref.)

Kadota, H., 1956: A Study on the Marine Aerobic Cellulose-decomposing Bacteria. *Mem. Coll. Agric. Kyoto Univ. 74*:1–128 (85 ref.)

Knight-Jones, E. W.; Walne, P. R., 1951: *Chromulina pusilla* Butcher, a Dominant Member of the Ultraplankton. *Nature, Lond., 167*:445–447 (17 ref.)

Kriss, A. E., 1952: Microbial Life in the Ocean Depths. *Adv. mod. Biol., Moscow, 34*:194–218 (65 ref.)

Kriss, A. E.; Rukina, E. A., 1952: Microorganisms in the Bottom Deposits of Ocean Regions. *Izvestiya Akad. Nauk SSSR, Ser. Biol.,* 6:67-79 (28 ref.)

McBee, R. H.; McBee, Virginia H., 1956: The Incidence of Thermophilic Bacteria in Arctic Soils and Waters. *J. Bact., 71*:182–85 (12 ref.)

Lindstrom, E. S.; Lewis, S. M.; Pinsky, M. J., 1951: Nitrogen Fixation and Hydrogenase in Various Bacterial Species. *J. Bact. 61*:481–487 (18 ref.)

Morita, R. Y.; ZoBell, C. E., 1955: Occurrence of Bacteria in Pelagic Sediments Collected During the Mid-Pacific Expedition. *Deep-Sea Res. 3*:66–73 (16 ref.)

Oppenheimer, C. H.; ZoBell, C. E., 1952: The Growth and Viability of Sixty Three Species of Marine Bacteria as Influenced by Hydrostatic Pressure. *J. Mar. Res. 11*:10–18 (9 ref.)

Pine, M. J.; Barker, H. A., 1954: Studies on the Methane Bacteria. XI. Fixation of Atmospheric Nitrogen by *Methanobacterium omelianskii. J. Bact. 68*:589–91 (10 ref.)

Renn, C. E., 1936: The Wasting Disease of *Zostera marina.* I. A Phytological Investigation of the Diseased Plant. *Biol. Bull., Woods Hole, 70*:148–58 (19 ref.)

——— 1937: Bacteria and the Phosphorus Cycle in the Sea. *Biol. Bull., Woods Hole, 72*:190–95 (8 ref.)

Rodina, A. G., 1956: Aquatic Spirillae Fixing Molecular Nitrogen. *Mikrobiologiya, Moscow, 25*:145–49 (6 ref.)

Sisler, F. D.; ZoBell, C. E., 1950. Hydrogen-utilizing, Sulfate-reducing Bacteria in Marine Sediments *J. Bact. 60*:747–56 (34 ref.)

——— 1951: Nitrogen Fixation by Sulfate-reducing Bacteria Indicated by Nitrogen/Argon Ratios. *Science 113*:511–12 (4 ref.)

Sparrow, F. K., 1936: Biological Observations on the Marine Fungi of Woods Hole Waters. *Biol. Bull., Woods Hole, 70*:236–63 (12 ref.)

Sverdrup, H. U.; Johnson, M. W.; Fleming, R. H., 1942: "The Oceans". Prentice-Hall, New York, 1087 pp.

Tarr, H. L. A., 1954: Microbiological Deterioration of Fish Post Mortem, Its Detection and Control. *Bact. Rev. 18*:1–15 (132 ref.)

Van Niel, C. B., 1936: On the Metabolism of the *Thiorhodaceae. Arch. Mikrobiol.* 7:323–358 (17 ref.)

Waksman, S. A., 1933: On the Distribution of Organic Matter in the Sea Bottom and the Chemical Nature and Origin of Marine Humus. *Soil Sci. 36*:125–147 (22 ref.)

——— 1934: The Role of Bacteria in the Cycle of Life in the Sea. *Sci. Mon. 38*:35–49 (33 ref.)

Waksman, S. A.; Reuszer, H. W.; Carey, Cornelia, L.; Hotchkiss, Margaret; Renn, C. E., 1933: Studies on the Biology and Chemistry of the Gulf of Maine. III. Bacteriological Investigations of the Sea Water and Marine Bottoms. *Biol. Bull., Woods Hole, 64*:183–285 (6 ref.)

Wakman, S. A.; Vartiovaara, U., 1938: The Adsorption of Bacteria by Marine Bottom. *Biol. Bull., Woods Hole, 74*:56–63 (11 ref.)

Wüst, G., 1950. Die grössten Tiefen des Weltmeeres in kritischer Betrachtung. *Erde, Berl., 3*:203–14 (25 ref.)

ZoBell, C. E., 1941. Apparatus for Collecting Water Samples from Different Depths for Bacteriological Analysis. *J. Mar. Res. 4*:173–188 (28 ref.)

——— 1942: Microorganisms in Marine Air. *In:* Aerobiology. *Publ. Amer. Ass. Advanc. Sci. 17*:55–68 (59 ref.)

——— 1943: The Effect of Solid Surfaces upon Bacterial Activity. *J. Bact. 46*:39–56 (50 ref.)

——— 1946a: "Marine Microbiology". Chronica Botanica, Waltham, Mass., 240 pp. (672 ref.)

——— 1946b: Studies on Redox Potential of Marine Sediments. *Bull. Amer. Ass. Petrol. Geol. 30*:477–513 (76 ref.)

——— 1952: Part Played by Bacteria in Petroleum Formation. *J. sediment. Petrol. 22*:42–9 (50 ref.)

ZoBell, C. E.; Conn, Jean E., 1940: Studies on the Thermal Sensitivity of Marine Bacteria. *J. Bact. 40*:223–38 (26 ref.)

ZoBell, C .E.; Morita, R. Y., 1957a: Barophilic Bacteria in Some Deep Sea Sediments. *J. Bact. 73*:563–8 (20 ref.)

——— 1957b: Deep Sea Bacteria. *Galathea Rep. 1*:139–54 (30 ref.)

ZoBell, C. E.; Oppenheimer, C. H., 1950: Some Effects of Hydrostatic Pressure on the Multiplication and Morphology of Marine Bacteria. *J. Bact. 60*:771–81 (24 ref.)

ZoBell, C. E.; Rittenberg, S. C., 1948: Sulfate Reducing Bacteria in Marine Sediments. *J. Mar. Res.* 7:602–17 (72 ref.)

ADDED IN PROOF

Among the many papers that have appeared since this article was prepared for the Symposium on Marine Microbiology are the following of outstanding significance:

Brisou, J., 1955: "La Microbiologie du Milieu Marin". Éditions Médicales Flammarion, Paris, 272 pp. (167 ref.).

Kriss, A. E., 1959: "Marine Microbiology (Deep Water)". Academy of Science USSR, Moscow (In Russian), 452 pp. (450 references having Russian titles and 146 in other languages).

Prevot, A. R., 1958: Utilité de la Bactériologie Marine dans le Présent et l'Avenir. *Bull. Inst. océanogr. Monaco 1114*:1–22 (50 ref.).

Wood, E. J. F., 1958: The Significance of Marine Microbiology. *Bact. Rev. 2*:1–19 (133 ref.)

ZoBell, C. E., 1957: Annotated Bibliography on the Ecology of Marine Bacteria. *Geol. Soc. Amer., Mem.* 67:1035–40 (85 ref.)

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MICROBIOLOGY OF OIL

by

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MICROBIOLOGY OF OIL*

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Virtually all commercial deposits of oil occur in ancient marine sediments, where microbes appear to affect its origin, chemical composition, preservation, and migration. Probably most pronounced are the effects of microbial activity upon source sediments of petroleum; particularly the organic fraction generally believed to be the mother substance of oil. Under certain conditions crude oils or products refined therefrom are attacked by bacteria and allied micro-organisms. Such microbes may play a part in the recovery of oil from natural formations, and microbial methods may be applicable to the discovery of oil. Sadly lacking, though, are quantitative data to assist the geologist or chemist in assessing the overall importance of bacteria.

COMPOSITION OF CRUDE OILS

Crude oil or petroleum consists of complex mixtures of gaseous, liquid, and solid hydrocarbons with lesser amounts of non-hydrocarbon constituents containing sulphur, oxygen, nitrogen, phosphorus, and at least 15 metallic elements. Petroleums from different geological provinces, fields, pools, wells, or depths may differ in density, colour, and chemical composition (Gruse and Stevens, 1942).

The average range in the chemical composition of crude oils from different parts of the world is as follows:

	Per cent by Weight		Per cent by Weight
Carbon	82·2–87·1	**Oxygen**	0·1 –4·9
Hydrogen	11·7–14·7	**Nitrogen**	0·05–1·2
Sulphur	0·1– 5·5	**Metallic elements**	0·01–0·08

Among the metallic elements found in the ash of many oils are calcium, magnesium, iron, copper, nickel, and vanadium (Bonham, 1956). Vanadium is believed to occur as a porphyrin complex of biological origin (Hodgson, 1954). Almost invariably present in crude oils are optically active compounds – a class of compounds produced only by living organisms as far as is known.

Aliphatic hydrocarbons of the alkane or paraffin series range in complexity from methane (CH_4) to molecules having up to 94 carbon atoms ($C_{94}H_{188}$). Naphthenes of the polymethylene series range from cyclopropane (C_3H_6) to cycloparaffins having up to 30 carbon atoms in their rings ($C_{30}H_{60}$). From 10 to 40 per cent by weight of oils consists of aromatic hydrocarbons or the benzene series. Commonly occurring are benzene (C_6H_6), methylbenzene or toluene ($C_6H_5CH_3$), dimethylbenzenes or xylenes ($C_6H_4CH_3CH_3$), naphthalene ($C_{10}H_8$), anthracene ($C_6H_4(CH)_2C_6H_4$), phenanthrene ($C_{14}H_{10}$), and an indeterminate number of polycylic alkanes.

Sulphur in crude oils may be present as free sulphur, hydrogen sulphide, and in organic compounds, including thiols or mercaptans, alkyl disulphides, thiophenes, thiophanes, sulphones, and other complex cylic sulphides.

Oxygen occurs in phenols, cresols, fatty acids or their derivatives, naphthenic acids, resinous compounds, and asphaltic substances.

Nearly all oils contain small quantities of nitrogen. It occurs in pyridines, quinolines, carbazoles, pyrroles, indoles, and other complex forms. The absence of simple nitrogenous compounds commonly occurring in plant and animal remains from which oil is believed to be derived suggests microbial degradation processes. Natural gases associated with crude oils contain appreciable quantities of gaseous nitrogen (N_2) and from a trace to 0·2 per cent ammonia. Pyrobituminous material in oil shales contains up to 2 per cent nitrogen.

OCCURRENCE OF OIL

Oil pools have been discovered in formations of all geological ages from the Cambrian through the Pliocene (Levorson, 1954). Some oil has been found in Pleistocene strata, but whether it is indigenous or has migrated there from older formations is uncertain. Oil pools occur in rocks ranging in age from nearly a million to about 500 million years. The occurrence of little oil in rocks younger than 1 million years suggests that oil formation is a slow process.

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The oil and/or gas content of a single deposit or reservoir is called a pool. An oil field is made up of one or more pools closely related geologically or geographically. A basic geological requirement for oil pools is a porous or permeable body of rock, called the reservoir rock. It must be overlain by an impervious layer of roof rock and deformed or obstructed in such a manner as to trap the oil. There are many kinds of structural or stratigraphic traps.

Oil reservoirs consist of sedimentary rocks; commonly marine sandstones, limestones, and dolomite. Reservoir rocks may contain oil in amounts ranging from only a few parts per billion to a few barrels per ton. Reservoir fluids are made up of various admixtures of oil, gas, and water. These fluids occur in pores of reservoir rocks having radii averaging 20 to 200 microns in sandstones. Some pores are much larger in limestone and dolomite reservoirs. The pores are much smaller in oil shales, which consist of varying mixtures of complex organic matter in shale and clay.

Oil shales contain little or no free oil and not much water. Oil and gas are liberated from the pyrobituminous substances in oil shale upon heating to about 350° c. Significantly there is no evidence of bacteria indigenous to, or able to live exclusively on, oil shale, unlike findings for oil reservoir fluids. Many constituents of crude oil are thermolabile; being unstable at temperatures higher than 150° to 200° c suggests a relatively low temperature for the origin of oil.

RESERVOIR FLUIDS

Most oil and gas pools or reservoirs occur in aquifers, i.e., water-saturated rocks. Water fills the smaller interstitial or pore spaces and forms a film on sedimentary particles making up the reservoir rock. Interstitial water in oil reservoirs is seldom less than 10 per cent and may fill more than 50 per cent of the pore space. Besides the water held by capillary attraction or adhering to solid surfaces, there may be much water emulsified in oil. The main body of water, however, is under the oil pool or at its boundaries, the so-called bottom or edge water respectively. Having a density greater than most oils, water may percolate down through the reservoir.

Water associated with oil pools may be meteoric, connate, or a mixture of the two. Meteoric water from rain may permeate permeable rocks through bedding planes, fractures, or permeable layers. Most connate water is fossil sea water, often having a salinity considerably greater than sea water (Case *et al.*, 1942). The mineral content of oil-field waters ranges from less than 1 to 25 per cent, as compared with an average of 3·4 per cent for modern sea water. Sea water and all reservoir fluids that have been examined contain all the minerals required for the growth of microorganisms. The reaction is within the biological range, i.e., pH 6·8 to 8·4. The sulphate-chloride ratio of oil-field waters or brines is nearly always less than in sea water, a condition that could be caused by the activities of sulphate-reducing bacteria commonly found in oil-well brines.

THEORIES ON THE ORIGIN OF OIL

Many theories have been advanced to explain the origin of oil (Stevens, 1956). None accounts for all the facts and, indeed, it is unlikely that all oils have had the same mode of formation. There is little evidence to support the belief of Berthelot that free alkali in primordial earth reacted with carbonic acid to yield simple hydrocarbons, some of which combined under the influence of heat, pressure, and catalysts to form oil. Conceivably, small quantities of oil could have resulted from the polymerisation of acetylenes resulting from the reaction of metallic carbides with water, as proposed by Mendeleeff, but like most inorganic origin theories this one fits few of the facts. Similarly, cosmic origin theories, championed by Oparin (1943), are not tenable with the conditions of occurrence and characteristics of oil.

Hydrogen from organic sources plays an essential part in the origin of oil. Whether hydrogen from inorganic sources also contributes importantly to the formation of oil is less certain. Free hydrogen commonly occurs in minute amounts in igneous rocks. It may have been present in larger concentrations or at great depths in primordial earth. Hydrogen in appreciable quantities is emitted from volcanoes and it occurs in fumarole gases (Rankama and Sahama, 1950). Deep in the earth's crust, iron or its oxides might react with superheated steam to form hydrogen. The alpha particle bombardment of water frees hydrogen, and oil-bearing sediments are generally radioactive (Sheppard, 1944).

Regardless of its source, hydrogen is chemically rather reactive and physically extremely mobile. These properties, plus the ability of bacteria to oxidise hydrogen, may explain why free hydrogen is rarely found in natural gas, oil pools, or sedimentary materials (ZoBell, 1947). From 11·7 to 14·7 per cent by weight of oil consists of hydrogen as compared with only 7 to 10 per cent in marine organic matter from which oil is believed to be formed.

There seems to be general agreement among modern petroleum chemists and geologists that most, if not all, oil is primarily of organic origin (Cox, 1946). The organic remains of both animals and plants, probably mostly marine but maybe partly freshwater or terrestrial, are believed to be the main mother substance of oil. The organic matter may have been modified by bacteria, contact catalysts, surface-active substances, pressure, temperature, radioactivity, and/or other agencies by processes that appear to require considerable time. Although complex hydrocarbons in small amounts are common constituents of recent marine sediments (Stevens *et al.*, 1956), petroleum pools are mostly a million or more years old.

Modifications of the organic matter seem to have taken place and oil occurs primarily in marine sediments. Although there may have been some migration of oil, gas, or protopetroleum, the main bulk of oil appears to have been formed in or relatively near the places where the pools are found. Migration could be no more than a few thousand feet vertically or no more than a few miles (mostly less than 100) horizontally.

The hydrostatic pressure of the environments where oil is found or was formed is believed to be no more than 20,000 psi and mostly less than 10,000 psi. The temperature to which oil has been subjected is probably less than 150° C and the temperature of most oil pools is considerably less than 100° C. The temperature gradient of sedimentary rocks approximates 0·9° C per 100 ft; pressure increases with depth by about 50 psi per 100 ft. These conditions seem to rule out the possibility of high temperatures or pressures being essential for the conversion of organic matter into oil. They do not rule out the possibility of bacterial activities contributing to the process, as will be elaborated below.

Accepting the premise that oil originates from organic matter, it is almost axiomatic that bacteria contribute to the process, because virtually all kinds of organic matter are susceptible to microbial modification in marine sediments. Less certain is the extent to which bacteria affect the origin of oil and whether their action is essential or merely incidental to the process. Besides modifying organic matter deposited in source sediments of petroleum, bacteria produce certain hydrocarbons, oxidise others (ZoBell, 1950), create reducing conditions which may favour the formation and preservation of hydrocarbons (ZoBell, 1946b), and affect other properties of sediments (ZoBell, 1942).

BACTERIA IN MARINE SEDIMENTS

An abundant microflora representing many species occurs in marine bottom deposits (ZoBell, 1946a). Bacteria occur in greatest numbers at the mud-water interface in recently deposited sediments rich in organic matter. In such sediments the bacterial population ranges from 10^5 to 10^8 per gram of wet material. The number and varieties of viable bacteria and also the organic content of the sediment decrease with core depth or with increasing age of the deposits (ZoBell and Anderson, 1936; Anderson, 1940). Such findings in the field, including changes in the chemical composition of organic matter with core depth or age, coupled with observations on recent marine sediments incubated in the laboratory, strongly suggest that bacteria are responsible for changes in the organic content.

From 10 to 10^4 bacteria per gram have been detected in the recent sediments taken from core depths of 3 to 7·5 m representing material several hundred thousand years old (Rittenberg, 1940; Morita and ZoBell, 1955). In more rapidly deposited near-shore sediments only a few thousand years old, bacteria were detected at a depth of 30 m below the mud-water interface. How much deeper or in how much older sediments indigenous bacteria may occur is yet to be determined. Bacteria have been recovered from oil pools of great antiquity, but it is difficult to prove their indigeneity. In the first place it is difficult to obviate contamination from extraneous sources and, secondly, there are possibilities of microbial migration and the movement of reservoir fluids.

Bastin (1926), Gahl and Anderson (1928), Ginter (1930), Ginsburg-Karagitscheva (1933), Müller and Schwartz (1949), and several other investigators have reported finding bacteria in reservoir fluids taken from depths down to several thousand feet. Under the auspices of the American Petroleum Institute we collected with utmost precautions samples of reservoir fluids from 66 different formations 2,680 to 10,470 ft below the earth's surface. Sulphate-reducing bacteria were detected in 29 of the samples. Many of the bacteria would grow only when subjected to higher pressures and temperatures characteristic of the formations from which the samples were taken. This suggests, but does not prove, that the bacteria were indigenous to the oil-bearing formation, because they may have been introduced during drilling operations and become acclimatised to the higher pressures and temperatures. There is also nearly always the possibility of bacteria being carried into the formation by the movement of ground water. The numbers and kinds of bacteria detected in some of the samples establishes that bacteria have been reproducing *in situ* in the reservoir fluids. Finding no bacteria in non-bactericidal reservoir fluids shows that it is possible to collect samples aseptically.

Müller (1944) found bacteria in 13 out of 38 aseptically collected side-hole samples of oil sands and oil-bearing limestones. We have found bacteria in a good many, but not all, cores drilled from sulphur-limestone-anhydrite and oil-bearing rocks from depths to nearly 10,000 ft representing sediments from 10^6 to 10^8 years old.

In 1950 we obtained through the cooperation of the Shell Oil Company several core samples from an oil well being drilled in the Ventura, California, Field. The oil company engineers were eager to learn whether living bacteria were indigenous to this formation where there was evidence (Doig and Wachter, 1951) of bacterial corrosion of oil well casings at depths of several thousand feet. In order to minimise possibilities of contamination, a new well was drilled with alkaline ($pH > 11{\cdot}5$) drilling mud. At the well head, cores of oil-bearing sand about 3 in. in diameter and 8 to 18 in. long were dipped in boiling paraffin wax to destroy surface contaminants, to exclude atmospheric oxygen, and to retain the fluid content of the samples. Thus protected the core material was brought to the laboratory where radially central sub-samples were removed aseptically with heat-sterilised instruments. Viable sulphate-reducing bacteria were detected in most 0·1 and 0·01 g sub-samples of oil-bearing rock taken from strata 4,337 to 4,412 ft deep. No such bacteria could be detected in the alkaline drilling mud, and the bacteria differed from those ordinarily occurring in soil or associated with surface materials. The absence of heterotrophic aerobes indicated freedom from surface contamination. Unquestionably the sulphate-reducing bacteria were indigenous to the oil-bearing formations where found. Extensive tests demonstrated that the oil-bearing formations possessed all of the prerequisites for the growth of sulphate-reducing bacteria; including water, minerals, nutrients, energy sources, favourable pH, tolerable temperature, and other conditions. There was no way, however, to determine how long the bacteria had been present in the formation nor the extent of their activity *in situ* prior to disturbance by drilling operations.

These and similar observations establish the presence of viable bacteria – mostly non-sporulating anaerobes – in many oil pools. Not enough field work has been done to warrant generalisations regarding how commonly bacteria occur in oil pools or whether there is any correlation between the occurrence of bacteria and the properties of oil-bearing formations. In certain formations no living bacteria could be detected by most meticulous examinations.

Such negative findings demonstrate the feasibility of aseptically collecting samples under difficult conditions. Whether bacteria were present or active earlier in the geological history of these bacteria-barren formations is indeterminate.

MICROBIAL MIGRATION IN MARINE SEDIMENTS

Propelled by flagella or perhaps more important by protoplasmic extrusion during growth, bacteria tend to move through water-wet sediments. The rate of movement is rather slow ranging from a few microns to as much as a few centimetres per day. The rate is influenced by the nutrient content of interstitial fluids, the size of the pore spaces, the kind of bacteria, temperature, and many other factors. In certain formations through which water percolates, bacteria are effectively filtered out by various mechanisms.

As might be expected, bacteria do not migrate into an environment which is unfavourable for their growth. Extremes of temperature, pressure, salinity, pH, redox potential, toxic constituents, and adsorptive capacity of solids may constitute barriers to the migration of bacteria. There is no evidence that bacteria either move into or survive long in marine sediments lacking in nutrients essential for growth.

ACTION OF BACTERIA IN SEDIMENTS

There are many ways in which bacterial activities in recently deposited marine sediments affect geochemical properties and diagenetic processes (Beerstecher, 1954). Besides creating reducing conditions, affecting the redox potential (ZoBell, 1946b), reducing sulphates to sulphides (ZoBell and Rittenberg, 1948), and oxidising molecular hydrogen (ZoBell, 1947), the principal effect of bacteria is on the organic content of sediments. Virtually all kinds of organic compounds are susceptible to microbial modification in sediments. The general tendency is for proteins, lipids, and cellulosic components to be attacked to give simpler compounds such as carbon dioxide, methane, hydrogen sulphide, hydrogen, and ammonia.

Heterotrophic bacteria grow or reproduce at the expense of the organic compounds which they assimilate. Large quantities are consumed as a source of energy and an average of roughly one-third of the carbon content may be converted into bacterial cell substance. The latter consists largely of complex proteins and lipids. Following their death the less refractory bacterial protoplasm undergoes autolysis or degradation. The more refractory remainder, together with the modified remains of the originally deposited marine organic matter, constitutes humus. With increasing age and depth of burial, marine humus generally contains proportionately progressively decreasing percentages of oxygen, nitrogen, and sulphur. The direction and magnitude of these changes in the chemical composition of the carbonaceous constituents in marine materials as compared with crude oil are illustrated by data in table 1.

TABLE 1. Proximate Analysis of Carbonaceous Constituents in Some Marine Materials

—	Marine Sapropel	Marine Humus	Ancient Sediments	Crude Oils
	%	%	%	%
Carbon	45–52	52–58	60–75	82–87
Hydrogen	5–9	6–10	9–12	11–15
Oxygen	25–30	12–20	0·7–10	0·1–4·9
Nitrogen	9–15	2–5	0:5–2	0·05–1·2

Sapropel consists largely of the remains of marine plants and animals recently deposited at the mud-water interface. Marine humus is the organic matter found in cores of recent marine sediments ranging from 10 to 10^6 years old. Ancient sediments were represented by rocks exposed by man or by weathering and estimated to be from 10^6 to 10^8 years old. Exclusive of oil pools the total carbon content of sedimentary materials decreases with increasing geological age, but in the residual carbonaceous matter the carbon and hydrogen content increases as a result of decreasing content of oxygen, nitrogen, and sulphur.

The general tendency is for marine humus to approach the elementary composition of crude oil. Similar modifications of lesser magnitude result from the microbial degradation of marine organic matter maintained in the laboratory under anaerobic conditions. A small fraction of the residual carbonaceous material proves to be hydrocarbons similar to those characteristic of crude oil. According to Smith (1954) and Stevens *et al.* (1956), complex hydrocarbons are common constituents of recent marine sediments, the concentration increasing with age or depth of burial. Bacterial activity could account for these changes, but no one has shown that the changes depend upon bacteria.

PETROLEUM CONSTITUENTS PRODUCED BY BACTERIA

Methane in large quantities is produced by bacteria. Methane production occurs in many anaerobic environments where bacteria are present and active. From 5 to 25 per cent or more of the carbon content of certain organic compounds undergoing anaerobic fermentation may be converted into methane. This common constituent of natural gas and petroleum is also produced by the bacterial reduction of carbon dioxide in the presence of hydrogen (Barker, 1936; ZoBell, 1947):

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

If methane can help to explain the origin of oil, the microbiologist can account for its formation in sufficient quantity in widespread locations.

The bacterial production of ethane in small quantities has been reported by Neave and Busswell (1928), Rawn *et al.* (1939), and others. According to Davis and Squires (1954), gases produced by the microbial fermentation of cellulose contained, besides large quantities of methane, from 3·2 to 7 p.p.m. ethane, 3·9 to 4·7 p.p.m. ethylene, 0·06 to 0·14 p.p.m. propane, and 0·13 to 0·21 p.p.m. propylene.

A good many bacterial species produce as part of their cell substance carotene, flavorhodin, and other complex pigmented hydrocarbons having the empirical formula $C_{40}H_{54-58}$ (Porter, 1946). Although these unsaturated hydrocarbons are not necessarily associated with petroleum, they are susceptible to hydrogenation and some of these compounds do have a benzene nucleus. Phenol, cresol, and other aromatic compounds commonly occurring in crude oil are produced by marine bacteria from the degradation of certain amino acids and proteins (Stone *et al.*, 1949; Updegraff, 1948).

Incorporated in the cells of most bacteria are small amounts of liquid and solid hydrocarbons. From sulphate-reducing bacteria cultivated on fatty-acid medium we harvested ether-soluble unsaponifiable extracts amounting to 0·08 per cent by weight of the dried cells. Carbon and hydrogen analyses showed that the extracts corresponded closely to the chemical composition of hydrocarbons ranging from C_{10} to C_{25}. In several subsequent experiments cells of *Desulfovibrio* species cultivated on various organic substrates under difficult conditions were found to have converted from 0·002 to 0·15 per cent of the organic carbon consumed into liquid and solid hydrocarbons.

Autotrophic sulphate reducers, utilising molecular hydrogen as a sole source of energy and carbon dioxide or carbonates as the sole source of carbon, also produced appreciable quantities of hydrocarbons (ZoBell, 1945). Approximately 0·42 per cent of the carbon content of the cells was extracted as an oily substance, 26 per cent of which consisted of predominantly paraffinic hydrocarbons. From another batch of autotrophic sulphate reducers which had consumed 33·92 litres of H_2 was extracted 1,640 mg of oily material. Microchromatographic separations, spectral analyses, and elemental analyses indicated that 458 mg of the oily material consisted largely of paraffinic hydrocarbons, and there was presumptive evidence of the presence of 367 mg of aromatic compounds.

Evidence that from 0·03 to 0·95 per cent of the carbon content of certain other bacterial cells from marine materials consists of liquid and solid hydrocarbons has been cited by Stone and ZoBell (1952). The amount is adequate to account for the hydrocarbon content of recent marine sediments (Smith, 1954). Hydrocarbons from such sources could help to account for the origin of oil, but the amount would have to be supplemented substantially by hydrocarbons from other sources unless as yet undiscovered bacteria or cultural conditions result in far greater yields.

BACTERIAL LIBERATION OF OIL

An increase in the amount of liquid and solid hydrocarbons recoverable from diatoms undergoing degradation by anaerobic bacteria has been recorded by Clarke and Mazur (1941). While part of this hydrocarbon may be produced by the bacteria, most of it was probably merely released from the diatom matrix by the bacterial decomposition of the protein, lipid, and carbohydrate structures. Similarly, bacteria are believed to be instrumental in the release of bound hydrocarbons from the decomposing remains of plants and animals, many of which are known to contain hydrocarbons (Chibnall *et al*., 1934; Sanders, 1937). Hydrocarbons thus released would be free to migrate and to accumulate in oil pools.

ZoBell (1952) has described a second mechanism by which bacteria may liberate oil by dissolving carbonate or sulphate rocks on which oil is absorbed. Besides releasing adherent oil the bacterial dissolution of such sedimentary materials may favour the flow and accumulation of oil by the formation or enlargement of void spaces and channels.

The formation of carbon dioxide, methane, or hydrogen in microtraps or elsewhere in oil-bearing sediments is another mechanism by which bacteria may promote the liberation, migration, and accumulation of oil.

MICROBIAL MODIFICATION OF OIL

Under favourable conditions, virtually all kinds of hydrocarbons are susceptible to attack by bacteria, yeasts, or fungi imperfecti (ZoBell, 1946c; 1950). Nearly 200 microbial species representing 40 genera have been shown to oxidise hydrocarbons. Among the substances shown to be oxidised by microbes are several pure hydrocarbons ranging in complexity from methane to anthracene, as well as a great variety of waxes, tars, asphalts, crude oils, petrols, kerosenes, lubricating oils, and other petroleum products. Besides microbial cell substances synthesised at the expense of the hydrocarbons oxidised, the principal oxidation products appear to be carbon dioxide and lesser amounts of organic acids, alcohols, and other intermediate compounds.

Most active in oxidising hydrocarbons are species of *Pseudomonas, Mycobacterium, Proactinomyces, Micrococcus, Bacterium, Bacillus, Sarcina, Serratia, Penicillium,* and *Aspergillus.* They have been shown to be active only in the presence of free oxygen or nitrate, which restricts the environments where they could be expected to modify oil. There is little or no free oxygen or nitrate below the topmost few millimetres of organic-rich sediments or in reservoir fluids. Whether there are other oxygen donors to provide for the oxidation of hydrocarbons in the absence of free oxygen or nitrate has not been demonstrated except for certain sulphate-reducing bacteria which slowly oxidise some of the higher (C_{12} to C_{31}) paraffinic hydrocarbons and a few aromatic compounds.

The widespread occurrence of hydrocarbon-oxidising bacteria in soil, sediments, and water suggests that they probably destroy or modify large quantities of oil or its components in aerobic environments. Of practical importance is the disappearance of oil from surface sediments, soil, and natural waters. Also petroleum or products refined therefrom may be susceptible to microbial modification when in contact with water such as, for example, machine coolants consisting of oil mixed with water or kerosene stored in tanks over water bottoms. To what extent bacteria may modify oil after its burial or formation in anaerobic environments is a subject for speculation.

According to Tausson and Aleshina (1932), certain sulphate-reducing bacteria tend to convert paraffinic hydrocarbons into naphthenic compounds. Tausz (1919) noted an increase in the asphaltic residue of Mendoza crude oil from an initial content of 0·3 per cent to 5·2 per cent as a result of prolonged bacterial activity under controlled laboratory conditions of experimentation. Maliyantz (1935) attributed observed decreases in the sulphur content of Russian crude oils to the selective action of sulphate-reducing bacteria.

The work of Tausson and Shapiro (1934) is representative of the observations of several workers who have demonstrated that bacterial activity affected the physical appearance, saponification number, iodine number, density, index of refraction, and other properties of petroleum held in the presence of free oxygen and water with dissolved minerals essential for bacterial growth. In the absence of water, bacteria have no effect on oil. From this it follows that after individual droplets of oil coalesce and collect in sufficient quantity to present a limited surface, the danger of destruction or microbial modification decreases.

In our laboratories at La Jolla experiments of 12 years' duration are in progress during which time strictly anaerobic sulphate-reducing bacteria have altered the properties of oil barely beyond the limits of recognized experimental errors. Definitely the bacteria have grown, reduced sulphate, and produced hydrogen sulphide, thus showing that oil components have been oxidised. Observed changes in the appearance, amount, and density of the residual oil, however, are so small that these changes might be attributed to the presence of bacterial protoplasm, emulsification of oil in water or water in oil, adsorption, loss of volatile constituents, or to experimental errors or artefacts.

PRESERVATIVE ACTION

Although bacterial activities might result in the destruction or modification of oil in certain sediments, elsewhere they may help to protect it from oxidation. The most obvious protective action is the consumption of free oxygen and the creation of reducing conditions. Likewise early in the history of oil microbes may produce antibiotics or other bacteriostatic substances which inhibit the growth of oil-oxidising organisms. Such bacteriostatic substances have been detected in source sediments of petroleum, but whether the presence of such substances is purely coincidental or prerequisite to the accumulation of oil is highly problematical.

Toxic metabolic products of bacteria, notably hydrogen sulphide, or the depletion of essential nutrients undoubtedly tend to limit bacterial activity. In a closed system such as a petroleum deposit bacterial activity would be self limiting by these factors. A state of dynamic equilibrium would soon be established in which the rate of reproduction or metabolism would be limited by the rate at which essential nutrients reach the bacteria and toxic products are carried away. All rates might be affected by the movement of reservoir fluids, but at best the rates are believed to be extremely slow.

A good many samples of reservoir fluids, including both crude oils and oil-well brines, have been examined for their growth-inhibiting or growth-promoting properties. Generalisations are difficult because there are so many kinds of microbes, fluids, and experimental conditions. Most reservoir fluids contain substances or possess properties which render them inhibitory or even lethal to many microbial cultures owing to the presence of phenols, benzene, hydrogen sulphide, high salinity and heavy metals. We have yet to find, however, a reservoir fluid which was either bactericidal or bacteriostatic for all bacteria. From this it might be inferred that reservoir fluids have a selective action on the growth of bacteria.

REFERENCES

ANDERSON, D. Q., 1940: Distribution of Organic Matter in Marine Sediments and Its Availability to Further Decomposition. *J. Mar. Res. 2*: 225–35.

BARKER, H. A., 1936: On the Biochemistry of the Methane Fermentation. *Arch. Mikrobiol.* 7: 404–19.

BASTIN, E. S., 1926: The Problem of the Natural Reduction of Sulphates. *Bull. Amer. Ass. Petrol. Geol. 10*: 1270–99.

BEERSTECHER, E., 1954: "Petroleum Microbiology". Elsevier Press, New York, 375 pp.

Bonham, L. C., 1956: Geochemical Investigations of Crude Oils. *Bull. Amer. Ass. Petrol. Geol.* 40: 897–908.

Case, L. C. *et al.*, 1942. Selected Annotated Bibliography on Oil-field Waters. *Bull. Amer. Ass. Petrol. Geol.* *26*: 865–81.

Chibnall, A. C., *et al.*, 1934: The Constitution of the Primary Alcohols, Fatty Acids, and Paraffins Present in Plant and Insects Waxes. *Biochem. J.* *28*: 2189–208.

Clarke, H. T.; Mazur, A., 1941: The Lipids of Diatoms. *J. biol. Chem.* *141*: 283–89.

Cox, B. B., 1946: Transformations of Organic Material into Petroleum Under Geological Conditions (The Geological Fence). *Bull. Amer. Ass. Petrol. Geol.* *30*:645–59.

Davis, J. B.; Squires, R. M., 1954: Detection of Microbially Produced Gaseous Hydrocarbons Other than Methane. *Science* *119*: 381–82.

Doig, K.; Wachter, A., 1951: Bacterial Casing Corrosion in the Ventura Field. *Corrosion* 7: 212–16.

Gahl, R.; Anderson, Belle, 1928: Sulphate-reducing Bacteria in California Oil Waters. *Zbl. Bakt., Abt. II*, *73*: 331–38.

Ginsburg-Karagitscheva, T. L., 1933: Microflora of Oil Waters and Oil-bearing Formations and Biochemical Processes Caused by It. *Bull. Amer. Ass. Petrol. Geol.* *17*: 52–65

Ginter, R. L., 1930: Causative Agents of Sulphate Reduction in Oil-well Waters. *Bull. Amer. Ass. Petrol. Geol.* *14*: 139–52.

Gruse, W. A.; Stevens, D. R., 1942: "The Chemical Technology of Petroleum". McGraw-Hill, New York, 733 pp.

Hodgson, G. W., 1954: Correlation of the Crude Oils of Western Canada by the Vanadium and Nickel Content of the Oils. *Oil in Canada* 6: 28–32.

Levorsen, A. I., 1954: "Geology of Petroleum". Freeman, San Francisco, 703 pp.

Maliyantz, A. A., 1935: Bacteriological Method of Desulphurizing Crude. *Azerbaidzh. neft. Khoz.* 6: 89–93.

Morita, R. Y.; ZoBell, C. E., 1955: Occurrence of Bacteria in Pelagic Sediments Collected During the Mid-Pacific Expedition. *Deep-Sea Res.* *3*: 66–73.

Müller, A., 1944: Researches in the Bacteriology of Petroleum. *Doctorate Diss.*, Technisch Hochschule Karlsruhe, Baden, 35 pp.

Müller, A.; Schwartz, W., 1949: Untersuchungen zur Erdölbakteriologie I. *Arch. Mikrobiol.* *14*: 291–308.

Neave, S. L.; Buswell, A. M., 1928: Treatment and Disposal of Distillery Slop by Anaerobic Digestion Methods. *Industr. Engng. Chem.* *20*: 837–838.

Oparin, A. I., 1943: "The Origin of Life". Dover Publications, New York, 270 pp.

Porter, J. R., 1946: "Bacterial Chemistry and Physiology". John Wiley, New York, 1073 pp.

Rankama, K.; Sahama, T. G., 1950. "Geochemistry". Univ. Chicago Press, Chicago, 912 pp.

Rawn, A. M.; Bańta, A. P.; Pomeroy, R., 1939: Multiple-stage Sewage Sludge Digestion. *Trans. Amer. Soc. Civ. Engrs.* *104*: 93–132.

Rittenberg, S. C., 1940: Bacteriological Analysis of Some Long Cores of Marine Sediments. *J. Mar. Res.* *3*:191–201.

Sanders, J. M., 1937: The Microscopical Examination of Crude Petroleum. *J. Instn. Petrol. Tech.* *23*: 525–73.

Sheppard, C. W., 1944: Radioactivity and Petroleum Genesis. *Bull. Amer. Ass. Petrol. Geol.* *28*: 924–52.

Smith, P. V., 1954: Studies on Origin of Petroleum. Occurrence of Hydrocarbons in Recent Sediments. *Bull. Amer. Ass. Petrol. Geol.* *38*: 377–404.

Stevens, N. P., 1956: Origin of Petroleum—a Review. *Bull. Amer. Ass. Petrol. Geol.* *40*: 51–61.

Stevens, N. P.; Bray, E. E.; Evans, E. D., 1956: Hydrocarbons in Sediments of Gulf of Mexico. *Bull. Amer. Ass. Petrol. Geol.* *40*: 975–83.

Stone, R. W.; Machamer, H. E.; McAleer, W. J.; Oakwood, T. S., 1949: Fermentation of Tyrosine by Marine Bacteria. *Arch. Biochem.* *21*: 217–23.

Stone, R. W.; ZoBell, C. E., 1952: Bacterial Aspects of the Origin of Petroleum. *Industr. Engng. Chem.* *44*: 2564–567.

Tausson, W. O.; Aleshina, W. A., 1932: Über die bakterielle Sulfatreduktion bei Anwesenheit der Kohlenwasserstoffe. *Mikrobiologiya, Moscow,* *1*:229–61.

Tausson, W. O.; Shapiro, S. L., 1934: The General Trend of the Process of Oxidation of Oil by Bacteria. *Mikrobiologiya, Moscow,* *3*: 79–87.

Tausz, J., 1919: Über die Einwirkung von Microorganisms auf Roherdöle. *Petroleum, Berl.*, *15*: 553–55.

Updegraff, D. M., 1948: The Production of Phenol and Para-cresol by Marine Bacteria. *J. Bact.* *57*: 555–64.

ZoBell, C. E., 1942: Changes Produced by Microorganisms in Sediments after Deposition. *J. sediment. Petrol.* *12*: 127–38.

——— 1945: The Role of Bacteria in the Formation and Transformation of Petroleum Hydrocarbons. *Science* *102*: 364–69.

——— 1946a: "Marine Microbiology". Chronica Botanica, Waltham, Mass., 240 pp.

——— 1946b: Studies on Redox Potential of Marine Sediments. *Bull. Amer. Ass. Petrol. Geol.* *30*: 477–513.

——— 1946c: Action of Microorganisms on Hydrocarbons. *Bact. Rev.* *10*: 1–49.

——— 1947: Microbial Transformation of Molecular Hydrogen in Marine Sediments, with Particular Reference to Petroleum. *Bull. Amer. Ass. Petrol. Geol.* *31*: 1709–51.

——— 1950: Assimilation of Hydrocarbons by Microorganisms. *Advanc. Enzymol.* *10*: 443–86.

——— 1952. Part Played by Bacteria in Petroleum Formation. *J. sediment. Petrol.* *22*: 42–49.

ZoBell, C. E.; Anderson, D. Q., 1936: Vertical Distribution of Bacteria in Marine Sediments. *Bull. Amer. Ass. Petrol. Geol.* *20*: 258–69.

ZoBell, C. E.; Rittenberg, S. C., 1948: Sulfate-reducing Bacteria in Marine Sediments. *J. Mar. Res.* 7: 602–17.

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On the Thermal Unrest in the Ocean

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Abstract

Rossby (1937, 38) has argued from theoretical grounds that there should be a great deal of thermal unrest in the deep ocean, partly due to variable wind-stresses associated with storms. Defant (1936, 1950, etc.) has suggested that internal tidal waves are a practically ubiquitous feature of the ocean, and has presented many analyses of rather short series of observations in evidence. As Haurwitz (1954) has indicated, the chief uncertainty involved in all discussions to date has been the result of the series of observations being too short: often only a few days. The purpose of this paper is to present a preliminary analysis of portions of temperature data obtained since Dec. 8, 1954 on two resistance thermometers located on the bottom off Bermuda at depths of 50 and 500 meters, the data being recorded regularly for several years now. The analysis for tidal periods, inertial periods, and shorter periods of the Brunt-Väisälä type is described.

I. Introduction

In two pioneer studies of the response of the ocean to transient wind-stresses, Rossby (1937—38) demonstrated theoretically that internal inertial gravity wave motions are induced in the deep stratified layers of the sea, thus suggesting a mechanism for stirring deep water. These theoretical results are of fundamental importance as indicative of a process of mixing which may play a central role in the general circulation of the deep ocean: " —because of the variability of the surface stresses it appears probable that vigorous inertia oscillations must develop in stratified media and express themselves as a marked intensification of the large scale horizontal turbulence . . ." (Rossby 1938, p. 248). These investigations stimulated theoretical studies by Cahn (1945), and others, the latest being a study by Veronis and Stommel (1956) which contains a summary of other studies.

In addition there is a very large literature concerning internal tidal waves in the ocean, among

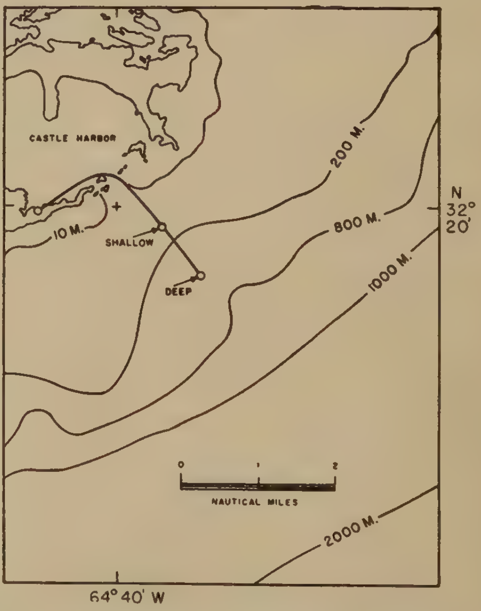

Fig. 1. Bathymetric Chart of Portion of Bermuda showing approximate location of the shallow and deep thermistors, the cable, and of the shore installation.

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[1] Contribution No. 954 from the Woods Hole Oceanographic Institution and No. 229 from the Bermuda Biological Station.

[2] Contribution from the Scripps Institution of Oceanography, new series. 1116

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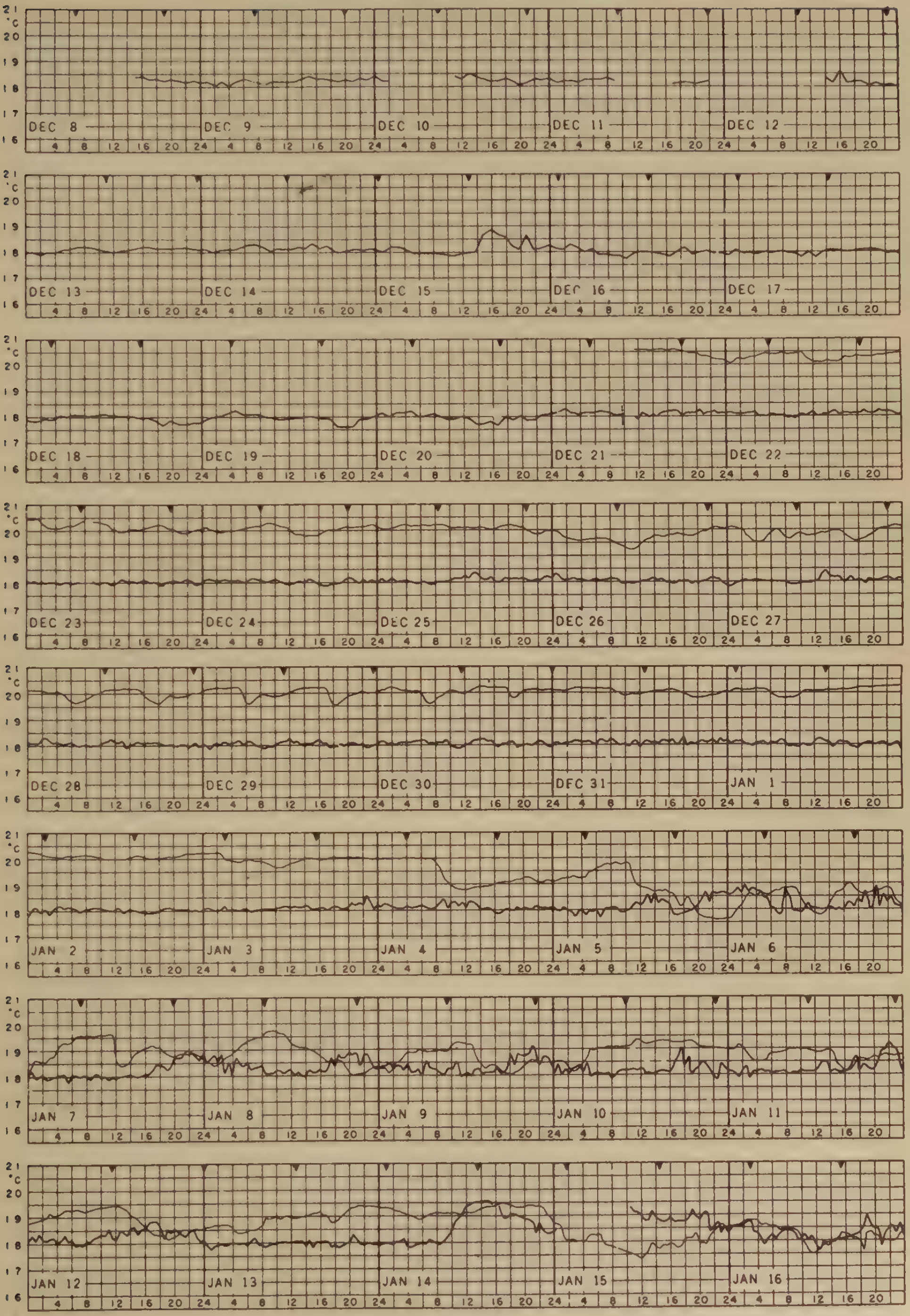
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Fig. 2a.

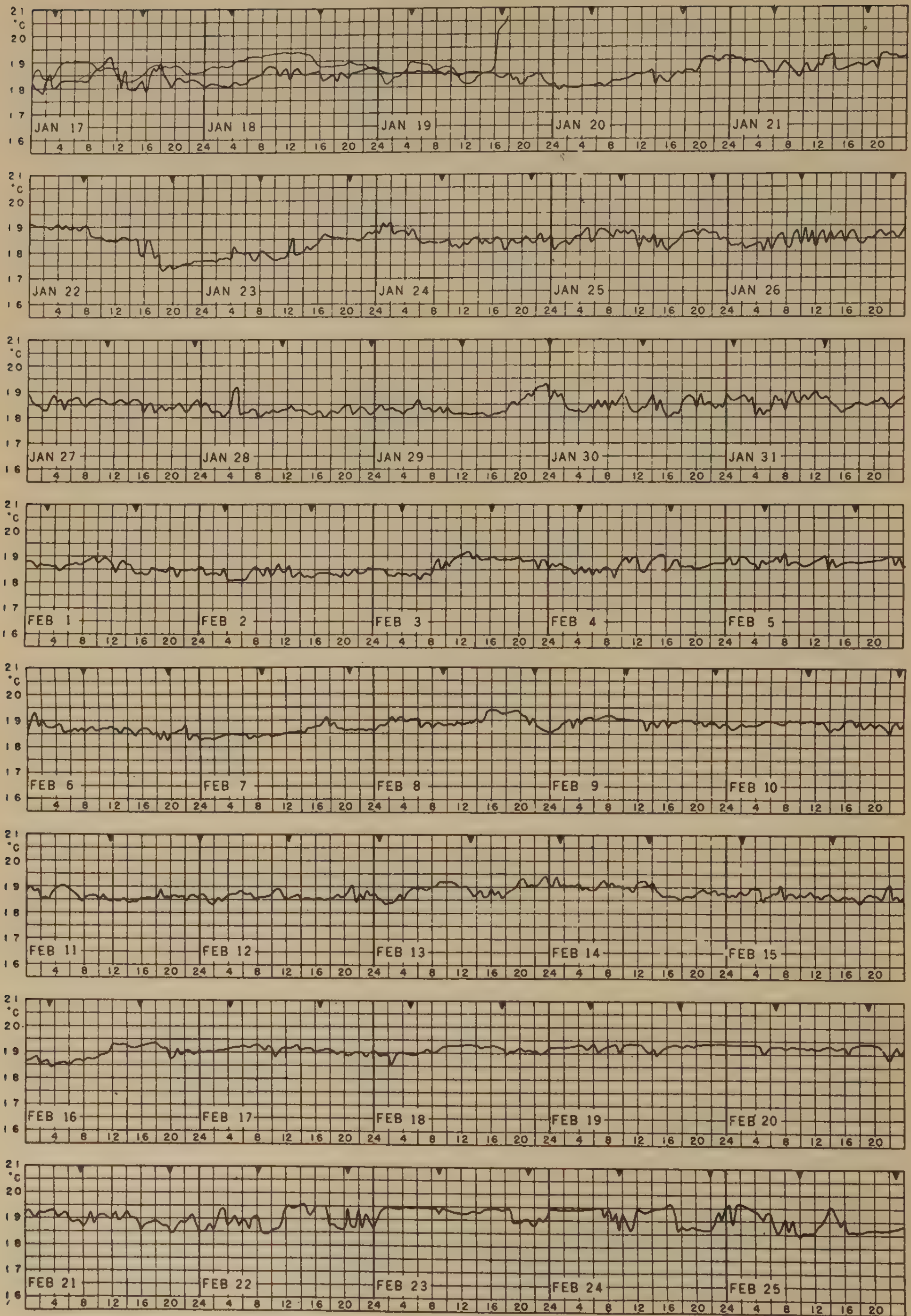

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Fig. 2b.

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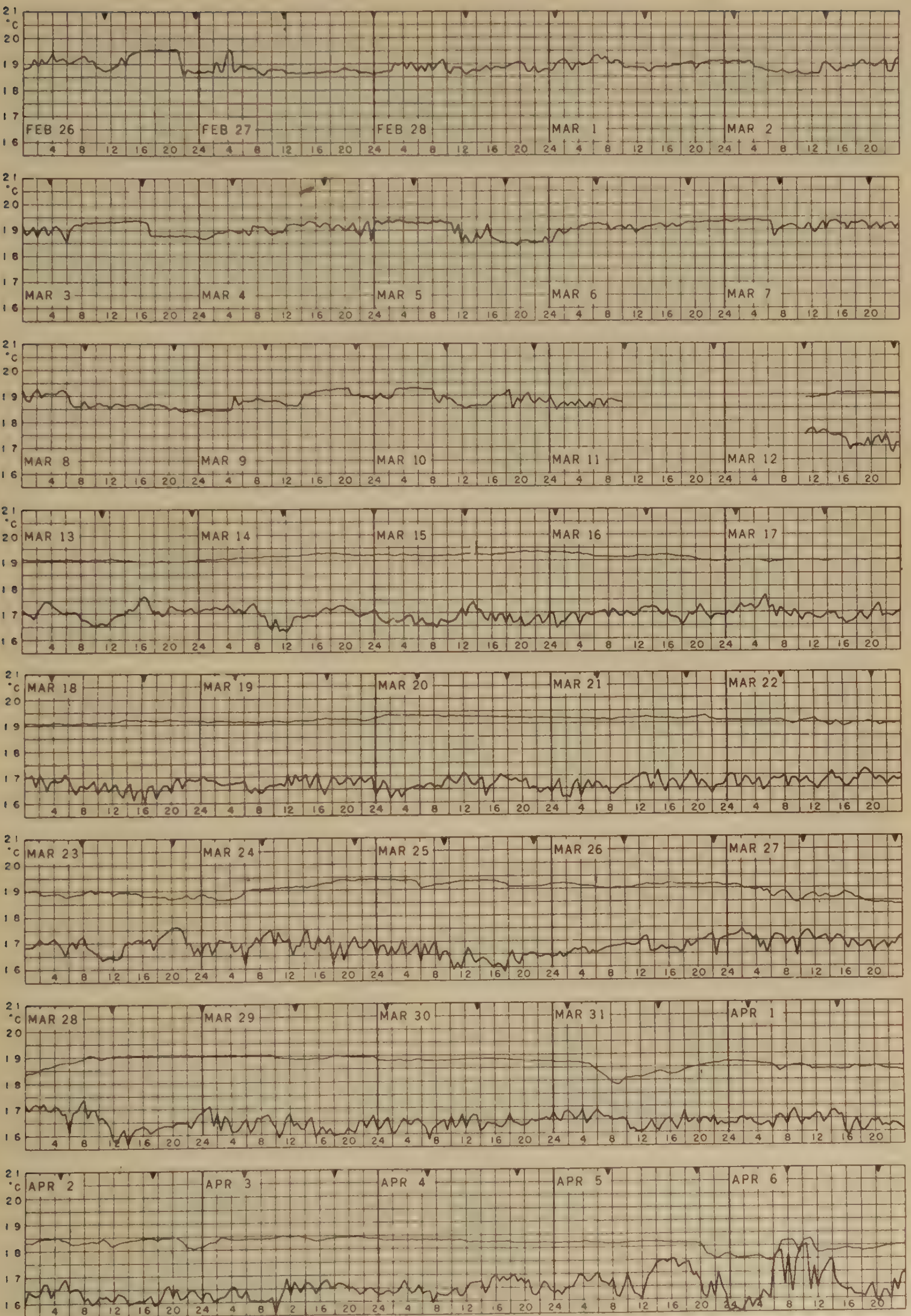
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Fig. 2c.

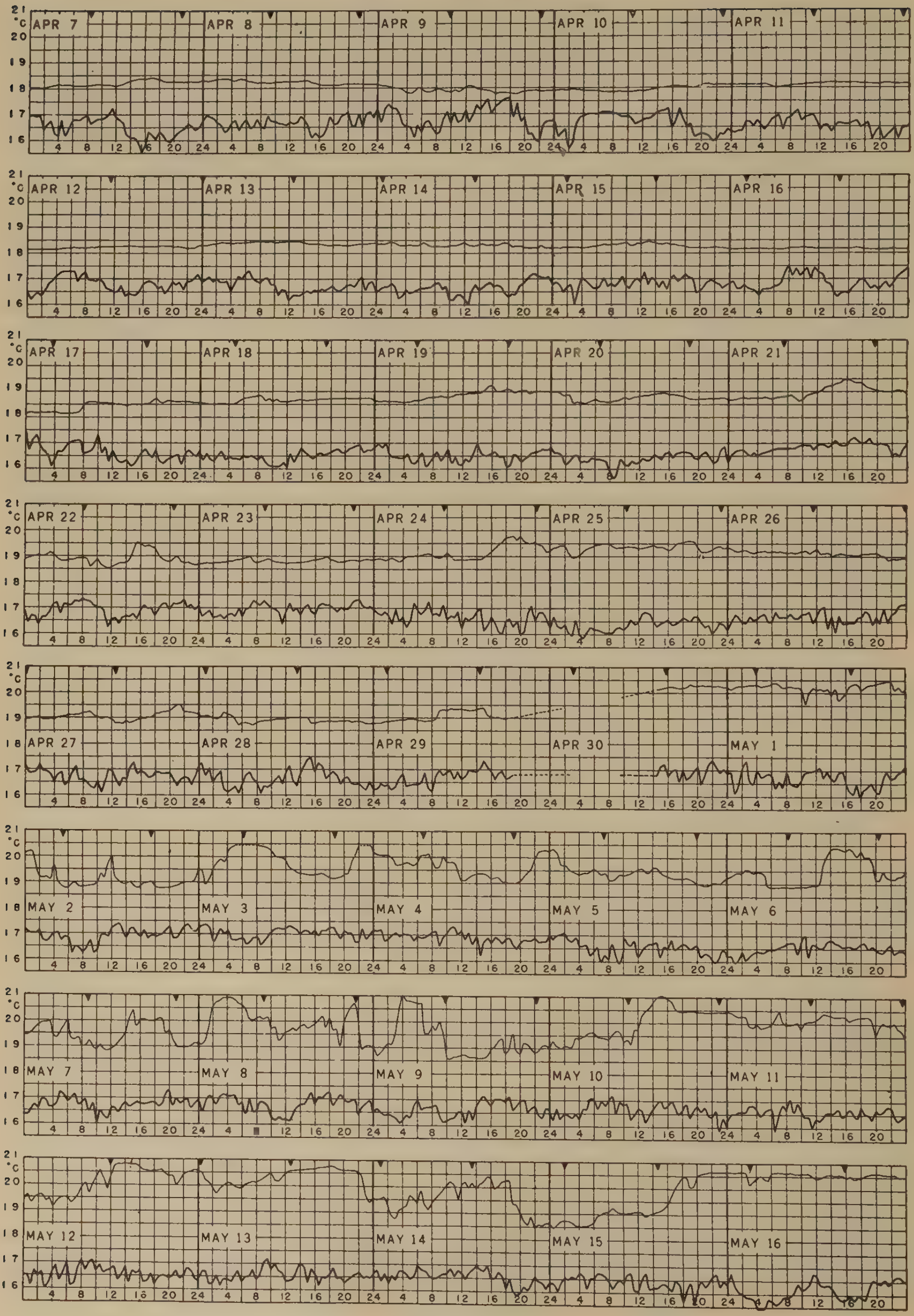
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Fig. 2d.

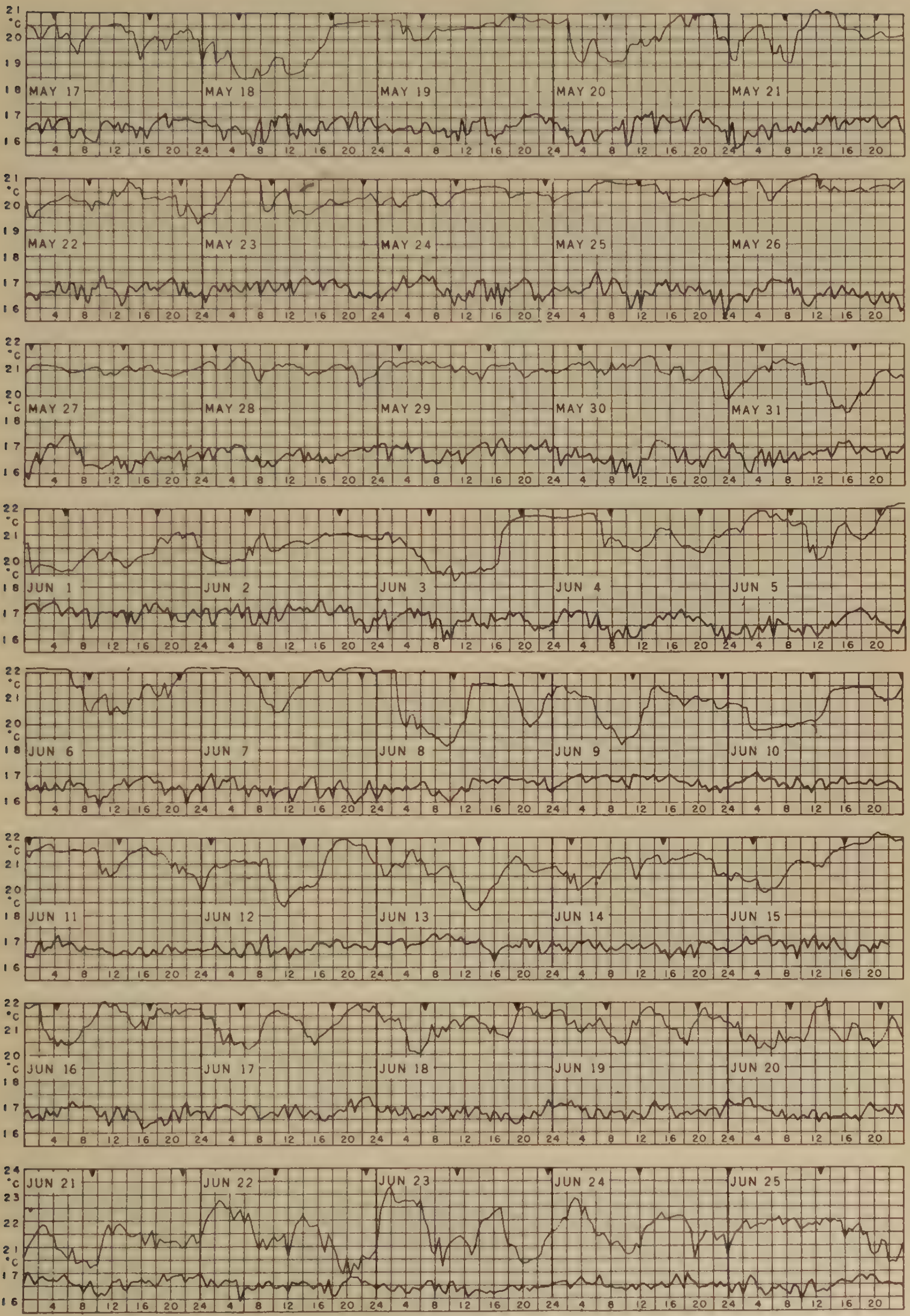
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Fig. 2e.

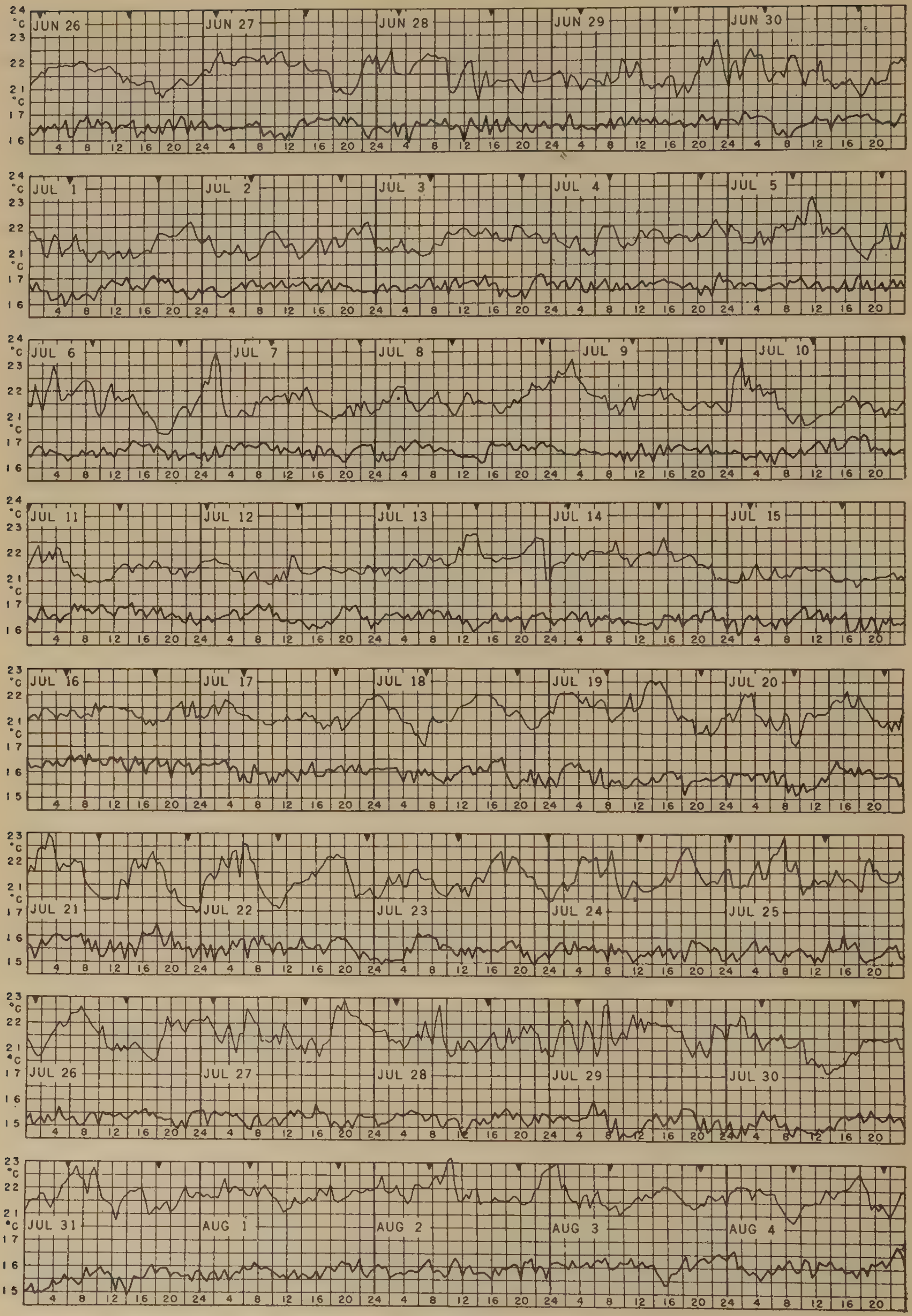
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Fig. 2f.

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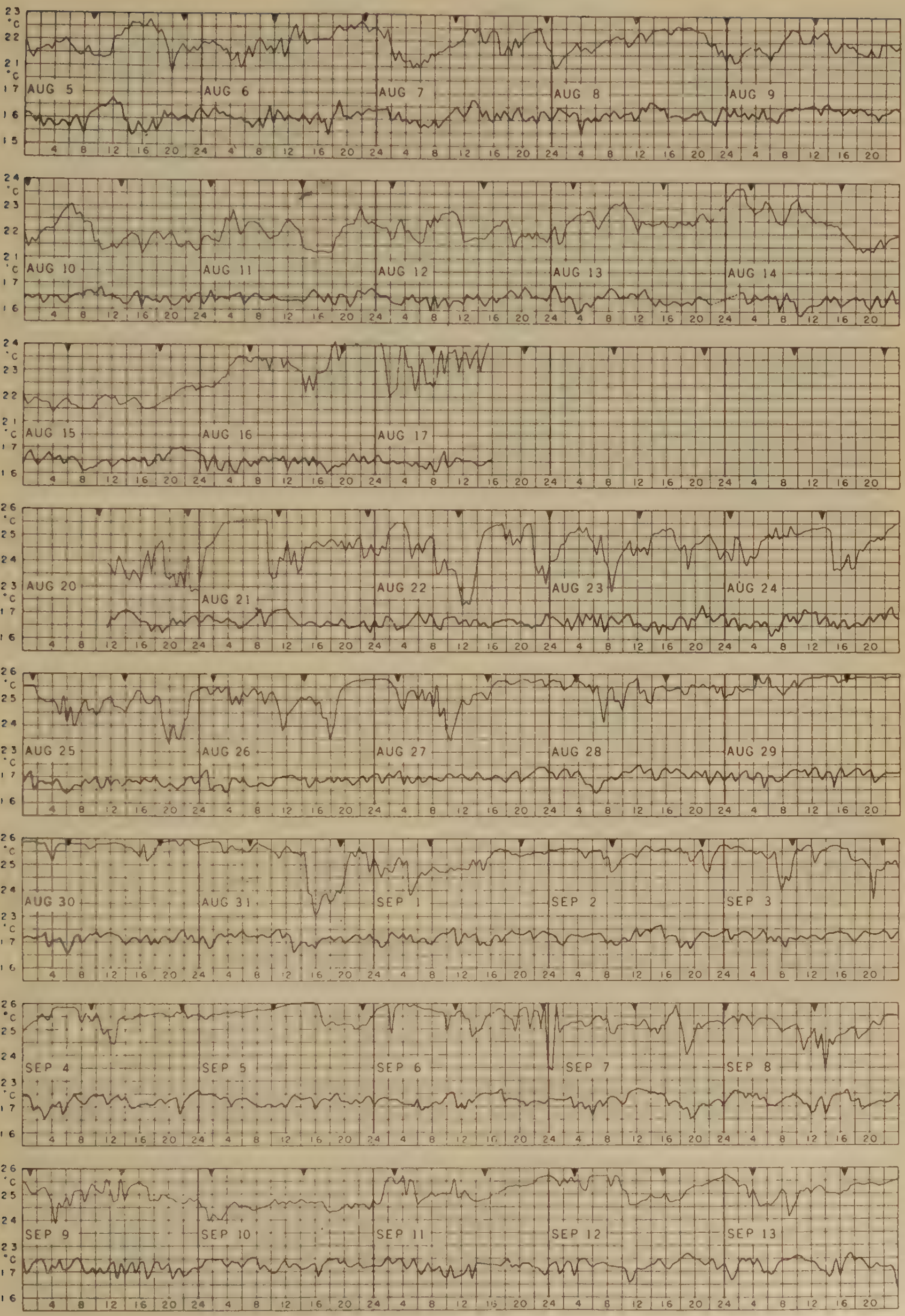
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Fig. 2g.

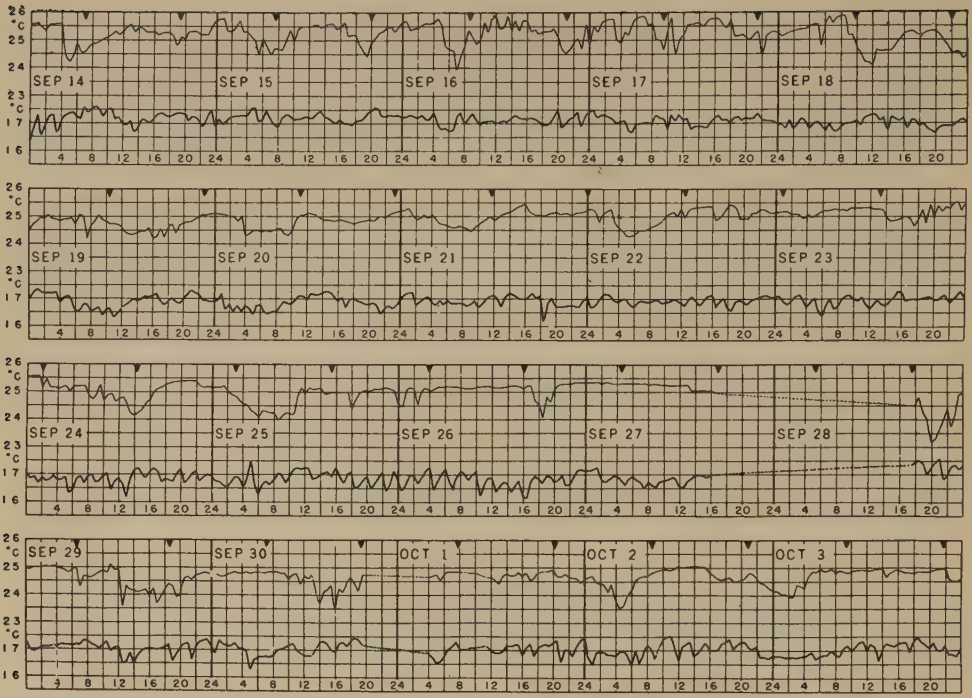

Fig. 2. The thermistor records from Dec. 8, 1954—Oct. 3, 1955 showing temperatures at the shallow and deep thermistors (light and heavy lines respectively). A new cable was installed March 12, with thermistors at slightly different depths. The small black triangles at the top show time of Bermuda high water, the time at the bottom is 60° W meridian time.

the most recent being papers by DEFANT (1950) and HAURWITZ (1954). These studies have been largely based upon the analysis of very short series of data, usually of no more than a few days' duration. As HAURWITZ (1954) has pointed out, one of the main obstacles to obtaining a more certain knowledge of the existence of internal waves in the ocean has been the lack of a truly long series of records of temperature in the deep water. As a first attempt to help supply such data, a submarine cable was laid from a recording Wheatstone bridge on the shore at Bermuda to two resistance thermometers offshore: one lying on the bottom at a depth of 50 meters, the other at 500 meters. (See Fig. 1 for location.) The shallow one was therefore approximately at the depth of the seasonal thermocline; the deeper one near the top of the main thermocline. Records have been obtained on this cable from Dec. 8, 1954 to Oct. 3, 1955 at intervals of one-half hour. From October 3, 1955 to May 7, 1957 records were obtained at five minute intervals. Since May 7, 1957 records have also been obtained from another resistance thermometer at 500 meters depth, but located five miles away from the original thermometer at a point further to the southwest along the coast of the island.

II. Qualitative presentation of data for the first period of observation

Portions of the cable data are presented in Fig. 2. The temperatures in degree Centigrade are given as ordinate, the dates and 60° W time are given as abscissa. The heavy line is the temperature as indicated by the deep thermometer: the light line indicates the shallow-element temperature. Occasionally, in order to keep the graph on scale, the origin of the ordinate is shifted (for example, see shift from June 20 to June 21, or July 15 to July 16). Also the scale is often broken in the middle to accommodate both thermistors (the first date at which the broken scale occurs is May 27). The little black triangles indicate time of predicted Bermuda high water. Two cables were used, one from December 8, 1954 to March 11, 1955; the second cable, from March 12 through October 3, 1955. The first cable was unarmored and soon began to fail—the shallow thermistor was lost on January 19, 1955, and it seems likely that the slow increase of the average deep temperature from 18.4° C near December 8 to 19.0° C in March, was also due to progressive cable failure. The deep thermistor of the second cable was placed somewhat deeper than that of the first as can be seen from the lower deep temperature beginning March 12. Readings at first were made every hour, but after December 22 were made every half hour. The readings were scaled off and replotted as shown in Figure 2.

In addition to the cable data, hydrographic data were also obtained over the same period by the PANULIRUS, the research vessel of the Bermuda Biological Station, and these data are exhibited in Figures 3 and 4. The vertical lines represent actual PANULIRUS stations—the rest of the contours are interpolated. Inasmuch as the variations of deep thermal structure indicated by the hydrographic data are no more than the high frequency variations revealed on the cable, it seems probable that the monthly fluctuations implied by the method of contouring in Figures 3 and 4 are simply the result of sampling errors. The seasonal variation above 500 meters is of course real. The main usefulness of the hydro-

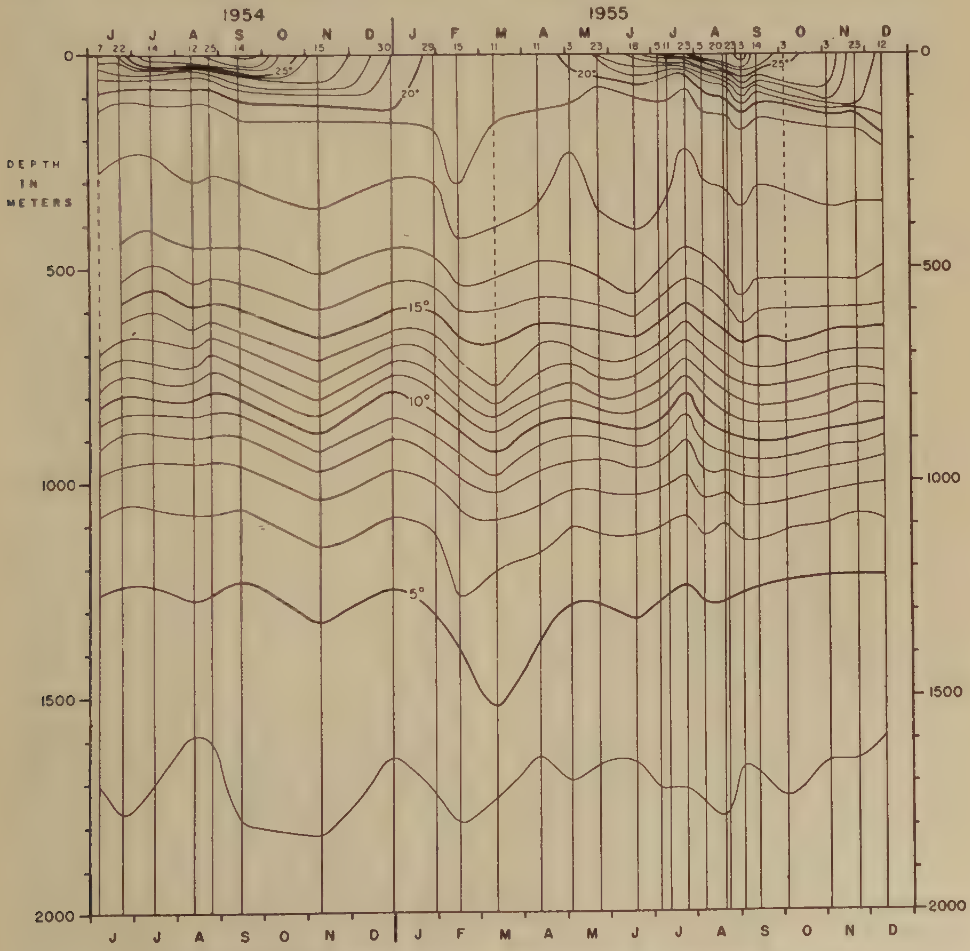

Fig. 3. Temperature as a funtion of time and depth by hydrographic station off Bermuda.

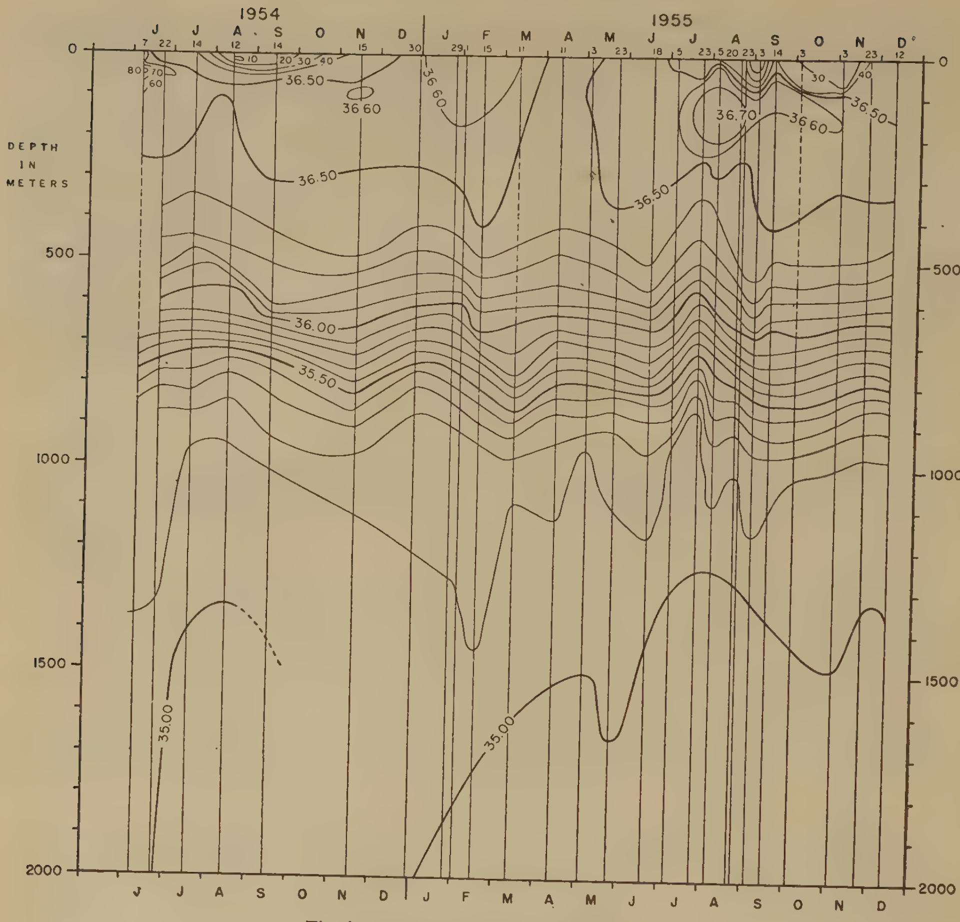

Fig. 4. Salinity corresponding to Fig. 3.

graphic data in Figures 3 and 4 is that it gives an idea of the *mean* vertical distribution of properties at various seasons near the cable, so that a rough estimate of vertical displacements of water can be obtained from the thermistor cable data.

From December 8 to January 3 there are few large disturbances on the shallow or deep thermistor. From December 26 to January 1 there is a slight drop in temperature of the shallow thermistor slightly after low water. Inasmuch as this is unassociated with any similar tidal fluctuation in the deep thermistor, and this is a period when the upper layer is fairly well mixed (Figure 4) we are inclined to explain this as evidence of cascading along the bottom slope of cold water from Castle Harbour (see BODEN 1952, 1953), which just manages to reach the shallow thermistor, but does not penetrate deeply enough to reach the deep one.

On January 2 a violent series of storms commenced over the North Atlantic, and by January 4, major disturbances at both thermistors were evident. During January 6 to 12 a pronounced long period, of somewhat less than 24 hours—perhaps an inertial period—can be seen on the deep thermistor record. Gradually the record becomes more and more confused or jagged—and during the period January 15 to February 15 even longer periods make an appearance. Above all, the deep records do not bear any resemblance to a tidal phenomenon—the phases appear to be quite randomly distributed with respect to time of high water. Isolated portions of the record (say February 24—25) look very much like tides—but they fail to persist and the similarity is doubtlessly fictitious. During this period the upper water became more and more mixed, the shallow thermistor was destroyed, and electrical tests indicated a gradual failure of insulation on the deep thermistor. On March 12 a completely new—and this time armored—cable was put into operation.

The violent temperature oscillations of the deep thermistor, starting on April 5 seem to be related to an intense storm just north of the island. During late April and May the growing amplitude of fluctuation on the shallow element appears to be associated with increasing vernal heating and growth of the seasonal thermocline (Figure 4), and gradually appears to be connected with surface tides. By mid-July there can be no doubt that the shallow temperature fluctuations are tied in with the surface tides. The deep thermistor appears to become more steady as the seasonal thermocline forms above it. Perhaps the seasonal thermocline shelters the main thermocline in some way, from disturbances at the surface—even hurricanes. Very remarkable long period fluctuations in deep temperature are indicated during the summer season, however, for example during July the average deep temperature dropped 1.5° C over a period of about three weeks and then rose again.

The hurricane which passed to the SW of Bermuda August 15th apparently caused the major disturbance at the shallow thermistor on August 16, without having any discernible effect at the deep one. A weak hurricane was passing to the east of Bermuda on August 31.

III. Preliminary search for tidal and inertial periods

A complete analysis of the large amount of data represented by the temperature records obtained off Bermuda is best carried out by cross-spectrum analysis. Such an analysis has been performed on the data obtained from November 1955 through February 1956. Its results are discussed in Section IV. But, since the records show some intervals during which periodicities appear fairly clearly it appeared worth while to make a simple preliminary investigation of the material.

In this section the results will be described which have been found in this manner. Attention has mainly been paid to the time interval up to the summer of 1955 when most of the work was done on which this section is based.

If the inspection of the temperature time graphs indicated that during a certain time interval a period or periods appeared in the data its statistical significance, and hence by inference its physical reality, was studied on the basis of periodogram analysis, harmonic analysis, and expectancy test. For some time intervals the tests for periodicities were made even though an inspection of the curves did not show that the periods to be looked for were present. This was done in particular for the lunar semidiurnal tidal period since it was thought that a demonstration of the presence or absence of this, the tidal period with the largest theoretical amplitude, was of intrinsic interest.

The methods employed here in the investigation of periodicities are all standard statistical procedures. They will therefore be described only very briefly in order to demonstrate specifically how they were used in this study. The temperatures are given at intervals of one-half hour. Since only periods of at least a few hours' duration are to be investigated the data were first smoothed by forming the means for each two-hour period. Only in the analysis of the 500 m records for the period 16—29 March 1955 such a smoothing was not performed.

With a few exceptions to be noted below for each selected record interval a periodogram analysis was first performed to determine the predominant amplitudes. Since no great accuracy was required a simplified method of periodogram analysis was used as a rule, as described by WHITTAKER-ROBINSON (1944, p. 356). In this simplification one takes for a given trial period the difference between the highest and lowest value in the line of mean values and plots this as abscissa.

After the predominant period or periods in the selected record interval have been determined the data were subjected to a harmonic analysis, with the determined period or an integral multiple of it as the analysis interval. Harmonic analysis will, of course, always give an amplitude for an assumed period even if the computation is based on random numbers. It is therefore necessary to ascertain how much larger the actually computed amplitude is than an amplitude resulting from an analysis of random numbers. This can be done by the expectancy test. Let A_i with the components a_i and b_i denote the amplitudes by harmonic analysis of the n individual periods.

Then

$$E^2 = \frac{1}{n^2} \sum_{i=1}^{n} A_i^2$$

the expectancy, is a measure of the amplitude of the mean period which should be expected in random data. Let $\overline{A}$ be the actual mean of the amplitudes,

$$\overline{A}^2 = \frac{1}{n^2} \left[\left(\sum_{i=1}^{n} a_i \right)^2 + \left(\sum_{i=1}^{n} b_i \right)^2 \right]$$

Then the probability p that

$$\overline{A} = kE$$

is

$$p = e^{-k^2}$$

If p is small it can be concluded that the computed mean amplitude is not likely to appear in random data; in other words it is likely that $\overline{A}$ is statistically and hence physically significant.

A difficulty in the application of the expectancy test in the present study is that the investigated time intervals are not selected arbitrarily, but because they showed fairly well developed temperature oscillations. This biased selection decreases the probability p, but it is impossible to state to what extent p is affected by this selection. It can only be said that with large p it is highly probable that the data are randomly distributed, and that the computed amplitudes are not significant. To be sure that a low value of p indicates non random data and significance of the amplitude one would wish to find lower values of p than in those cases when the data are not pre-selected.

In the following the analyses of the various intervals will be discussed briefly.

a) *6—18 January, 1955*

During this time some pronounced oscillations occurred at the 50 m and 500 m recorders. The periodogram analysis for the 50 m record suggested periods of 24 hours and 30 hours, for the 500 m level a period of 23 hours, close to the inertia period. Accordingly expectancy tests were performed for these periods, and also for a 12-hour period because of its proximity to the theoretically largest lunar tidal period. The results are summarized in Table I. An inspection of the harmonic coefficients of the 24-hourly oscillation at both levels for the individual days shows a much greater regularity during the first six days than later. Therefore, the expectancy test was also applied separately to this time interval. None of the computed probabilities is small enough to state that the periods under consideration are not statistical accidents, especially in view of the manner in which this time interval was selected for analysis. In particular the values for the 12-hour period indicate that the 12-hourly tidal period was not contained in the data. Further, the harmonic coefficients for the 12-hourly period, based on the temperature on the individual days, which are not reproduced here did not show the systematic phase change which would be present if a lunar period of 12 hours 25 minutes existed. At 500 meters depth the lower probability associated with the 23 hour period favors an inertial oscillation over a diurnal tide, at least during 6—11 January 1955, but the statistical significance of this result remains in doubt because of the selection of the data.

b) *16—29 March 1955; 1—29 June 1955*

Although the time interval from 6—18 January 1955 did not show either the 12-hourly or 24-hourly lunar tidal period it was thought that statistically significant values for the amplitudes of these two tidal oscillations might perhaps be obtained if a longer series of data were chosen. First, the temperatures registered at 500 meters during the epoch from 16 March to 29 May,

Table I. Expectancy Test, 6—18 January 1955, 50 m and 500 m

Period	50 meters			500 meters		
	Ampl.	Expect.	Prob.	Ampl.	Expect.	Prob.
30 hrs.	0.26° C	0.15° C	0.05	—	—	—
24 hrs.	0.15	0.13	0.33	0.13° C	0.10° C	0.18
12 hrs.	0.09	0.06	0.10	0.08	0.14	0.67
24 hrs.*	0.28*	0.16*	0.05*	0.23*	0.11*	0.013*
23 hrs.*	0.26*	0.17*	0.08*	0.22*	0.10*	0.009*

* First six days.

1955 have been studied. This time interval was chosen because about the middle of March 1955 a new and more satisfactory cable was installed. The data were plotted on a time graph with solar time as the abscissa. On this graph the upper lunar transits (local lunar noon) were marked so that the temperatures for each lunar hour could be read off without difficulty. For this particular computation no smoothing by averaging was performed here. The data were then combined into groups each of which consisted of four consecutive lunar days, in order to reduce the amount of computational work. Altogether 17 such groups were available; the period April 26—30 had to be omitted because of insufficient data.

The 17 four-day mean daily ranges were then harmonically analyzed. The results of the expectancy test for the harmonics 1 and 2 are shown in Table II.

Table II. Expectancy test for time interval 16 March —29 May 1955, 500 meters

Period length	Amplitude	Expectancy	Probability
24 lunar hours	0.038° C	0.026° C	0.10
12 lunar hours	0.034° C	0.020° C	0.27

The probabilities that the 24-hourly and especially the 12-hourly amplitudes are due to random data are large. Thus it must be concluded that these two main lunar periods are not present in these data. Because of the negative result for the 500-m depth the temperature at the 50-m depth has not been studied.

In order to see whether a different result would be obtained for another time interval an expectancy test for the two main lunar tidal periods was also made for 1—19 June 1955, both for the 50 and 500-m depths. The difference between lunar and solar time was allowed for by a rearrangement of the solar hours in the computation schedule. In order to reduce the numerical work the data were averaged in groups of four consecutive lunar days prior to the harmonic analysis. The results are summarized in Table III. Only the semidiurnal lunar period at 50 m can possibly be considered as appearing in the temperature data. The amplitudes of the diurnal lunar period at both depths and of the semidiurnal lunar period at 500 m are not statistically significant.

Table III. Expectancy tests for time interval 1—29 June 1955, 50 m and 500 m

Depth	Period length	Amplitude	Expectancy	Probability
50 m	24 lun. hrs	0.12° C	0.14° C	0.51
50 m	12 lun. hrs	0.28° C	0.13° C	0.01
500 m	24 lun. hrs	0.012° C	0.031° C	0.85
500 m	12 lun. hrs	0.057° C	0.044° C	0.19

During this period the temperature at 500 m depth showed some pronounced oscillations. Therefore a simplified periodogram analysis was performed beginning with a period of 10 hours and extended in steps of two hours, to 42 hours (Fig. 5). The periodogram shows a peak for a period of 20 hours, and another one for 40 hours

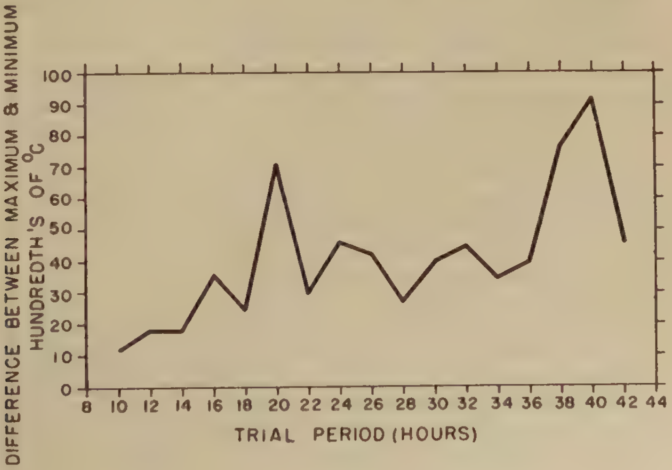

Fig. 5. Periodogram of temperature records at 500 m depth off Bermuda, April 5—13, 1955.

which is a reappearance of the maximum at 20 hours.

This 20-hour period is evidently not of tidal origin. The inertia period at the latitude of Bermuda is 22.4 hours, considerably longer than 20 hours. A direct expectancy test showed furthermore that a period of 22 hours is not indicated in the data (see Table IV below). Thus it must be concluded that the 20-hour period has no connection with the inertial period. It does not appear fruitful at this time to speculate on the physical origin of the 20-hour oscillation; it may be that it is excited by the storm in the vicinity of Bermuda at the beginning of the time interval under investigation, and that the length of its period is determined by the physical state of the waters around Bermuda. But this is admittedly pure speculation.

For the sake of completeness this same time interval has also been searched for periods of 24 and 12 hours because these periods are very close to the lunar tidal periods. The results together with the relevant expectancy test data for all the periods studied for this interval are shown in Table IV. The probabilities that the 24-hour and especially the 12-hour oscillations as expressed by their amplitudes are of real physical significance are evidently very low. Since it is actually the lunar tidal periods which are in general strongest and not the solar tidal periods it might be thought that the test is not conclusive since the analysis has been performed for solar hours. It is possible to apply a correction for the phase shift which arises if a set of data containing the lunar period is analyzed according to 24 solar hours. This has been done but the resulting corrections do not alter the computed probabilities significantly. Hence it appears that the lunar periods are definitely not observable during the time interval under investigation.

Table IV. Expectancy test for time interval 5—13 April 1955, 500 meters

Period length	Amplitude	Expectancy	Probability
20 hours . . .	0.31° C	0.13° C	0.003
22 hours . . .	0.09° C	0.12° C	0.613
24 hours . . .	0.16° C	0.12° C	0.14
12 hours . . .	0.05° C	0.09° C	0.70

d) *7—12 May and 3—7 June 1955, 500 m*

These time intervals were investigated because the temperature graphs showed some fairly regular oscillations during these times. Periodogram analyses extending from trial periods of 10 to 42 hours indicated peaks at 12 hours, 24 hours, and 36 hours. The expectancy test was performed only for the 12 and 24 hour periods because its result showed immediately that the periodogram peaks at 24 hours, and by inference those at 36 hours; are merely repetitions of the twelve-hour peak. The results of Table V make it appear possible that the 12-hourly periods are real, but it must be remembered that the time intervals were chosen because they showed regular oscillations. While the analysis was carried out according to solar time it is likely that the 12-hourly periods discussed here are in reality lunar 12-hourly periods, since the lunar tidal force is larger than the solar tidal force. If the lunar tides were more strongly developed and not as much disturbed by superimposed variations it would be possible to differentiate between lunar and solar tidal oscillations by studying the phase shift of the harmonic constants as determined for each day. But the superimposed noise makes this procedure inapplicable.

Table V. Expectancy tests for time intervals 7—12 May and 3—7 June 1955, 500 m

Epoch	Period length	Amplitude	Expectancy	Probability
7—12 May	24 hours	0.03° C	0.06° C	0.80
	12 hours	0.14° C	0.08° C	0.035
3—7 June	24 hours	0.07° C	0.07° C	0.32
	12 hours	0.23° C	0.12° C	0.019

In summary of the discussion in this section it can be said that from time to time periodicities appear in the record with periods whose lengths are 30, 24, 23, 20, and 12 hours. The 24-hourly and 12-hourly oscillations are presumably the lunar tidal periods, the period of 23 hours may be the inertial period (more accurately 22.4 hours at Bermuda). No explanation is offered for the 30 and 20-hourly periods. None of these periods can be regarded as definitely established, except perhaps the 12-hourly lunar tidal period at 50 m depth during June 1955 (Table III) whose chance occurrence has a probability of only one in one hundred. Other periods with equally low or lower probability, 20 hours

(Table IV), 23 hours (Table I) are not as significant because they were found in pre-selected data. Even the 12-hourly period is not always clearly indicated in the data, as shown by the expectancy tests. Physically, it would seem quite plausible that even these periodicities for which causes are known, such as the tidal and inertial periods, are not always clearly shown in the observation material because they may often be completely obscured by other periodic and unperiodic variations.

To make an over-all test concerning the reality of various periodicities in the Bermuda data it is necessary to extend the analysis to a larger body of data. It becomes then desirable to compute cross spectra using high-speed computers. This part of the investigation will now be discussed. The resulting gain of higher resolution and statistical reliability is offset in part by the implied assumption that many months of record can be treated as a "stationary time series".

IV. Spectra of the records

A) THE METHOD

The method is essentially the one given by Tukey (Tukey, 1949; Panofsky and McCormick, 1954). From the cosine transform of the autocorrelations one obtains the spectra S_d and S_s of the deep and shallow temperature records. The cosine and sine transforms of the cross-correlation are the cospectrum C and quadrature spectrum Q. From these we obtain the coherence Co and phase Θ between the two records according to

$$Co^2 = \frac{C^2 + Q^2}{S_d S_s}, \qquad \tan \Theta = \frac{Q}{C},$$

with Θ taken between 0° and 180° for positive Q, and between 180° and 360° for negative Q. With this convention Θ designates the phase *lead* of shallow record with respect to the deep one.

For each of the six analyses the four quantities S_d, S_s, Co^2 and Θ are plotted without smoothing against frequency in cycles per hour. The highest frequency in Fig. 6 is 2.5 c.p.h., exactly half the sampling frequency of 5 readings per hour. The frequency range from 0 to 2.5 c.p.h. is divided into $m = 62$ equal frequency intervals $\Delta f = 2.5/62 = .0432$ c.p.h. (see Table VI). S_d, S_s, Co^2 and Θ are plotted for all but the first of these intervals.

S_d and S_s are in units of °C²/c.p.h. This can be interpreted as follows. The r.m.s. value of the deep record A: 1 is .25 °C (Table VI); the variance thus equals .0625 °C². The plotted values give the contribution towards this variance from a unit frequency band (width 1 c.p.h.) centered at the plotted frequency. The reliability of the plotted values depends on the degrees of freedom, $\gamma = (2\,N/m) - {}^1/_2$, where N is the total number of values used in the analyses. Analyses A: 1, A: 2, and A: 3 are each based on 2,355 readings, thus $\gamma = 75$. The vertical arrows on Fig. 6 and 7 give the 95 per cent confidence limits. For 75 degrees of freedom these are 0.76 to 1.40; i.e., there is one chance in twenty that the correct value be less than 0.76 or larger than 1.40 times the computed value. The logarithmic plot enables one to plot a single "confidence arrow" for all values in an analysis.

The mean phase relation throughout the record length is given by Θ for each of the frequency bands. Co^2 is a measure of the variability in Θ at this frequency. If Θ were constant throughout the analyzed record, then $Co^2 = 1$; if it were randomly distributed, then $Co^2 = \Theta$. Clearly the reliability of the computed Θ depends on coherence. The 95 per cent confidence limits that Θ lies within the limits $\Theta - \Delta\Theta$ and $\Theta + \Delta\Theta$ are as follows (from Goodman, 1957):

Table VI. Information concerning the two charts that were analyzed. Data extend from Nov. 1955 to Feb. 1956

	Prefilter	Δf c.p.h.	E °C		N	ν
			deep	shallow		
A: 1 Nov. 9: 0800—Nov. 28: 2200 . . .	12^m H 12^m	.04032	.25	.11	2355	75
A: 2 Nov. 28: 2200—Dec. 18: 1200 . . .	12^m H 12^m	.04032	.31	.15	2355	75
A: 3 Dec. 18: 1200—Jan. 7: 0200	12^m H 12^m	.04032	.32	.22	2355	75
B: 1 Jan. 11: 1300—Feb. 2: 0700	12^m H 12^m	.04032	.25	.20	2610	84
A: 4 Nov. 11: 0500—Jan. 5: 0500	12^m L 48^m H 48^m	.001008	.28	.23	1650	53
B: 2 Jan. 13: 1000—Jan. 31: 1000 . . .	12^m L 48^m H 48^m	.01008	.29	.32	540	17

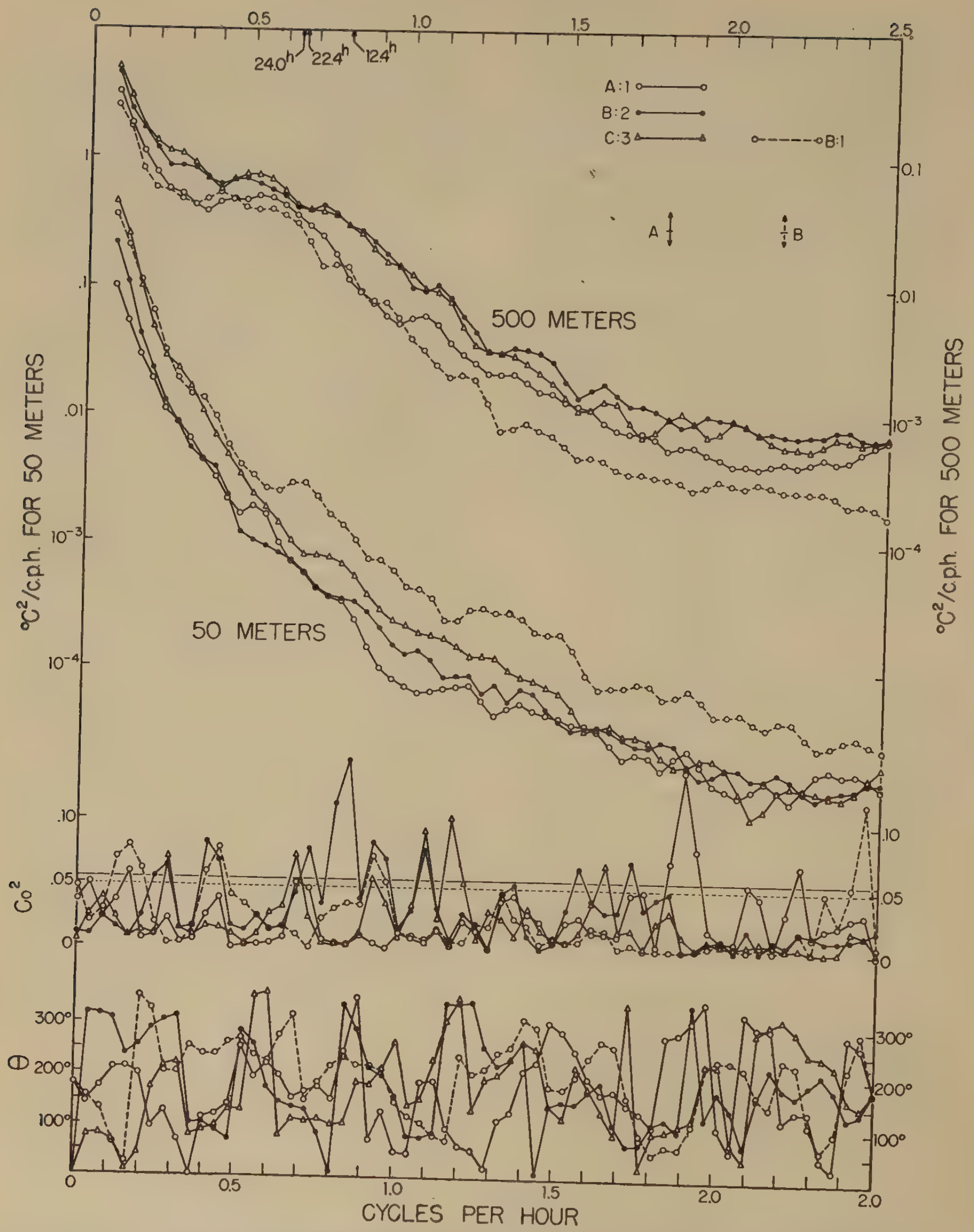

Fig. 6. Four co- and quadrature spectra designated by A: 1, A: 2, A: 3, B: 1 in Table VI. The spectral densities at 500 meters (right scale) and 50 meters (left scale) are displaced relative to one another by a factor 10. The arrows indicate the 95 per cent confidence limits. Approximate confidence limits on the coherence Co^2 between the records are given by the horizontal lines. Evidently there is no significant coherence, and accordingly the phase relation Θ between the records is not significant.

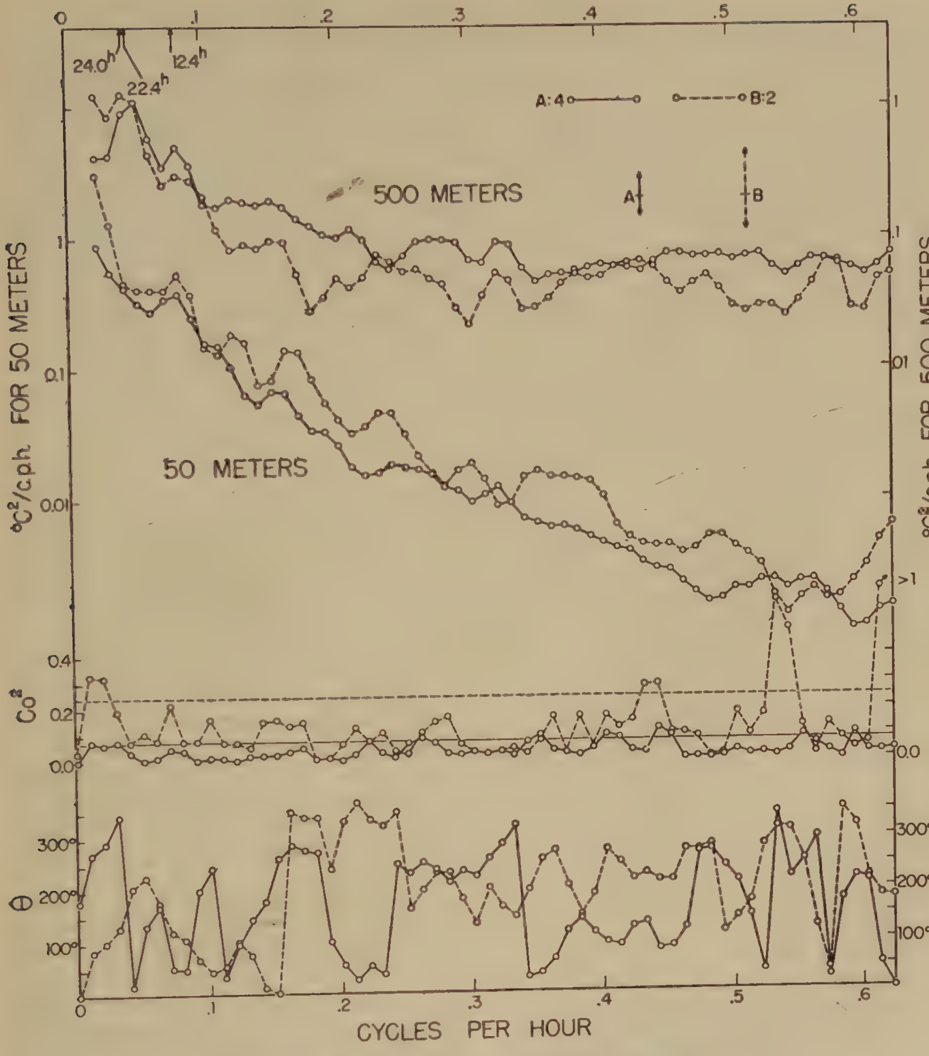

Fig. 7. Similar to Figure 6 except for a lower frequency range.

Table VII. Values of $\Delta\theta$ for stated coherence Co^2 and degrees of freedom

		ν			
		84	75	53	17
Co^2	.50	16°	17°	20°	40°
	.25	28°	30°	37°	—

The corresponding limits on Co^2 are roughly $4/\nu$, so that only the largest values of coherence are significant, and only for those can a meaningful phase relation be inferred.

The procedure adopted was as follows. Record A was read every 12 minutes to the nearest 0.01 chart-inch (0.005° C); each reading is in doubt by something like .02 chart inches (.01° C). The data were put on punchcards and a numerical high-pass filter applies (designated by $12^m H\, 12^m$ in Table VI). In this way long-term temperature drifts are suppressed without appreciably affecting the frequencies here under consideration. If the high-pass filtering were not done, then the spectrum would be seriously contaminated by the relatively high "energy" associated with this drift. Fifteen hours of record are lost at each end by virtue of the high-pass filtering. The remaining portion was split up into three equal lengths as shown in Table VI, and the spectrum analysis performed. Prefiltering was done on an IBM 650 computer, the spectrum on a Remington Rand 1103 computer.

In addition, the complete record was analyzed in another way in order to improve the resolution at low frequencies (Table VI, A: 4). By a suitable set of weighting functions the high-frequency wiggles were reduced, and the smoothed record tabulated at an interval of 48^m, four times that of the original record. This low-pass filtering was again performed on an IBM 650 computer. The 48^m readings were then high-passed and analyzed as before. The prefiltering is designated by 12^mL 48^mH 48^m in Table VI. The result is that the smoothed spectra (Fig. 7) extend only over one-fourth the frequency range as compared to the original spectra (Fig. 6), from 0 to 0.625 c.p.h. instead of 0 to 2.5 c.p.h. The reduced frequency range is again divided into 62 intervals, and in this way the frequency resolution is quadrupled. The improved resolution is at the expense of reliability. In the case of record A, the reduction in ν is moderate, from 75 to 53, because A: 4 is based on roughly three times the length of records as the other analysis. In the case of B the length of record was too short for subdivision, and the reduction in ν is severe, from 84 in B: 1 to 17 in B: 2. (Note the uncertainty arrows in Fig. 7.)

In any analyses based on observations at discrete intervals, the "aliasing problem" is severe (Tukey, 1949): frequencies in the vicinity of the sampling frequency appear in the alias of a low frequency. Thus for reading every 12^m a 13^m wave would have the appearance of $13^m \times 12^m =$ $= 156^m$ wave. The problem is particularly acute when going from the 12^m readings to the 48^m reading, and the low-pass filter is designed to alleviate the difficulty. First order corrections for aliasing were made for A: 4 and B: 2, and the final results were corrected for slight modifications due to filtering. The procedures are cumbersome and dull. A full discussion is in preparation (Munk, Snodgrass, and Tucker, in press).

B) THE RESULTS

i. *The high frequency cut-off*

For frequencies in excess of 0.75 c.p.h. all spectra drop towards high frequency by something like 10 db per octave, that is, somewhat more sharply than f^{-3}. The computed cut-off is actually weaker than the true cut-off for a number of reasons: (1) In any steep spectrum the calculation leads to a diffusion of spectral energy from the high to the low regions. (2) More important, random errors in chart reading introduce a white noise which materially boosts the high frequency values. Suppose the rms error is .02 chart inches = .01 °C. The error variance is then 10^{-4} °C^2, and if this is uniformly distributed across the entire range of frequencies, from 0 to 2.5 c.p.h., the resulting spectral density is $10^{-4}/2.5 = 4 \times 10^{-5}$ °C^2/c.p.h. This is roughly the value reached at the high frequency and by the shallow spectra. The deep spectra at the high frequency end are ten times higher and may be real. A reliable determination of the spectra for $f > 2$ c.p.h. would require some elaboration in the recording scheme.

In all events the monotonic high-frequency cut-off is a real feature and needs to be explained. For each of the four spectra the *trends* are reproducible within the limits of statistical uncertainty. Actual values may vary from record to record by a factor three. B: 1 record has the lowest densities of the deep spectra and the highest of the shallow spectra. A noteworthy feature is that the deep spectrum is ten times the shallow spectrum.

In a general way this can be accounted for in terms of the stability of the water column. A thorough analysis of the internal wave motions possible in the waters around Bermuda does not seem warranted by the available data. But certain conclusions can be drawn by means of the Väisälä (or Brunt) frequency,

$$N = \frac{1}{2\pi}\sqrt{\frac{g}{\varrho}\frac{d\varrho}{dz}}$$

Fig. 8 shows $N(z)$ for winter conditions in 1955. A maximum $N_m = 5.6$ c.p.h. at 200 meters is associated with the seasonal thermocline, a second, weaker maximum at 850 m with the permanent thermocline. N_s and N_d are local values of the frequency at the depths of the shallow and deep instruments, respectively. At any depth we should expect no frequencies larger than N_m; a greatly reduced spectral density for frequencies larger than the local Väisälä frequency, and a relatively large spectral density for frequencies less than the local Väisälä frequency. An extrapolation of the computed curves bears out the first prediction of no significant spectral density at 5.6 c.p.h.; the second prediction might account for the relative absence of high frequencies in the shallow record. The spectral densities at the local Väisälä frequencies is 10^{-3} °C^2/c.p.h. for both the deep and shallow records.

This geometric argument has been developed by Eckart (personal communication) and will be discussed in detail in his forthcoming book.[1] It would be out of place to reproduce the argument here. There is, however, some doubt concerning the applicability of the argument to a situation as complex as the one found at Bermuda, with two maxima of N. Judging by the three-layer case, one expects the oscillations at the two thermoclines to be only weakly coupled, with the shallow instrument responding largely to modes associated with the seasonal thermoclines, and the deep instrument to modes associated with the permanent thermocline. This situation could account for the virtual absence of coherence between the records. At no frequency range is there a significant coherence, and it is significant that this should be so.[2]

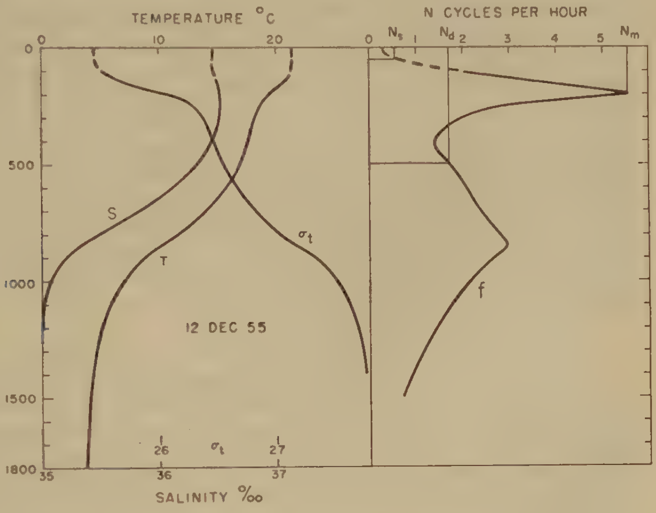

Fig. 8. The Väisäla (or Brunt) frequency $2\pi\,(g\varrho^{-1}\,d\varrho/dz)^{1/2}$ on December 12, 1955. The upper maximum (N_m = 5.6 c.p.h.) is associated with the seasonal thermocline; the lower, weaker maximum with the permanent thermocline; N_s and N_d are the local values of this frequency at the depths of the shallow and deep recorders, respectively.

ii. *The 0.5 c.p.h. plateau*

All four deep records show a weak maximum (or at least a plateau) of spectral density between 0.4 and 0.6 c.p.h. There is no corresponding feature on the shallow records. The feature can be seen on both the low and high-frequency spectra, and there can be no reasonable doubt of its reality. The surprisingly low frequency involved, 1 cycle in two hours, is an embarrassing aspect of the situation. Nowhere beneath the seasonal thermocline does the Väisälä frequency reach such low values, except depths below 2,000 m. Could it be that the Väisälä frequency associated with the deeper half of the ocean contributes appreciably to the thermal unrest in the permanent thermocline?

iii. *The lunar tide*

Both spectra show a peak for both the shallow and deep records at the frequency of the principal lunar tide (see Fig. 7). For the deep spectrum the area under the peak corresponds to roughly

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[1] The earliest discussion of the cut-off frequency (a far as we know) has been given by GROEN (1948).

[2] Widely separated low-frequency surface wave records have yielded coherences up to $Co^2 = 0.9$ (MUNK, SNODGRASS and TUCKER, in press). Two components of currents as determined by a long GEK series taken by J. Reid also had coherences up to 0.9.

.004 $^\circ C^2$ above background, somewhat more for the shallow spectrum. The corresponding amplitude is $\sqrt{.008} \approx 0.1$ °C, or 10 meters of vertical displacement. The internal tide contributes only a small fraction of the energy in the band centered at .008 c.p.h., and for that reason the coherence must remain low; still a coherent harmonic embedded in an incoherent noise could have been expected to give some enhancement in Co^2 at this frequency. The fact that it is not so indicates that the relative phase of the two instruments for the 12.4^h internal tides does not remain fixed!

With regard to the possible existence of discrete tidal modes, the present method of analyzing into relatively wide frequency bands cannot compete with the resolution obtained by Fourier Series methods employed in earlier parts of this paper.

iv. *Diurnal oscillation*

A significant peak in spectral density for the two shallow records at .04—.05 c.p.h. can be ascribed to either a 24.0^h tide or a 22.4^h inertial oscillation.

Whether or not this is due largely to internal tides could be decided by the use of the expectancy test. If the peak is due chiefly to inertial motion which decays in, say, tenperiods, then the resolution by the present method is adequate.

Remarks

The authors have tacitly assumed an explanation in terms of internal waves rather than drifting convection cells. To settle this point decisively the cross-spectrum of two records at 500 m depth would be required.

Acknowledgements

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REFERENCES

Cahn, A. J., 1945: An Investigation of the free oscillations of a simple current system. *J. Meteorology,* **2,** p. 113—119.

Defant, A., 1932: Die Gezeiten und inneren Gezeitenwellen des Atlantischen Oceans. *Wissensch. Erg. d. Deutschen Atl. Exp. »Meteor«,* 1925—27, Bd. VII, Teil I, 1—318.

— 1950: On the origin of internal tide waves in the open sea. *J. Mar. Res.* IX, **2,** 111—119.

Goodman, N. R., 1957: On the joint estimation of the spectra, cospectrum and quadrature spectrum of a two-dimensional stationary Gaussian process. *New York University: Scientific Paper* No. 10, Engineering Statistics Laboratory.

Groen, P., 1948: Contribution to the theory of internal waves. *Kon. Ned. Met. Inst. de Bilt. Med. en Verh.,* **2,** 11.

Haurwitz, B, 1954: The occurrence of internal tides in the ocean. *Arch. Meteor. Geophys. und Bioklimat,* **7,** 406—424.

Munk, W. H., Snodgrass, F. E., and Tucker, M. J., 1959: Spectra of low frequency ocean waves. To be submitted to the *Bulletin of the Scripps Institution of Oceanography* (in press).

Panofsky, H. A., and McCormick, R. A., 1954: Properties of spectra of Atmospheric turbulence at 100 meters. *O,. J. Roy, Meteor. Soc.,* **80,** 546—564.

Rossby, C.-G. 1937—38: On the mutual adjustment of pressure and velocity distribution in certain simple current systems. *Jour. Mar. Res.* Part I, **1,** 15—28, Part II, **1,** 239—263.

Tukey, J. W., 1949: The sampling theory of power spectrum estimates. *Symposium on applications of autocorrelation analysis to physical problems,* Woods Hole, Mass., 13—14 June 1949, p. 47—67 (printed by Office of Naval Research).

Veronis, G. and Stommel, H., 1956: The action of variable wind stresses on a stratified ocean. *Journ. Mar. Res.* **15,** p. 43—75.

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Climatic Records on the Ocean Floor

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Abstract

A close relation is found between the wind driven circulation in the Equatorial Current System in the Pacific, and the distribution on the ocean floor of minerals produced by organisms in the surface layer of the ocean. The large variations in time of rate of accumulation of such solids is discussed in terms of corresponding changes of trade wind intensity in the past. Special attention is given to the validity of time estimates, and a comparison is made between the Atlantic and the Pacific records.

Climatic changes on continents and in polar areas mostly have such catastrophic effects on the geological record that in a quantitative study the intensity and time factors involved are difficult to ascertain. The bottom deposits of the tropical ocean far away from continents and polar areas therefore appear promising as records of such climatic changes.

1. Significance of carbonate accumulation

The first attempt at a large-scale study of the stratification of such deposits was undertaken by W. Schott (1935), using the extensive material of sediment cores collected during the German Meteor-Expedition in the Atlantic Ocean. The areas studied by Schott are mostly covered with foraminiferal ooze, a sediment which essentially consists of a minor fraction of silicate minerals and varying amounts of calcium carbonate in the form of tests of foraminifera. These are protozoa, which are largely planktonic and live from the phytoplankton produced in the surface layer of the ocean. At reproduction or upon death, the calcareous tests sink to the bottom. Another contribution of sedimentary calcite comes from planktonic flagellates with minute calcareous plates, coccoliths, secreted from the protoplast. Due to the lack of saturation of the deep water with respect to calcium carbonate, a varying fraction of the accumulated carbonate goes back into solution in the bottom water. The final rate of accumulation of calcium carbonate is therefore found as the difference between the rates of production and dissolution of calcareous skeletal material.

The production of skeletal calcium carbonate in the surface layer of the ocean is an unknown function of food supply, temperature (acting through the carbon dioxide system and perhaps also in a direct way), competition factors and other unknowns. The food supply, in its turn, appears in the tropical ocean to be regulated by the intensity of vertical mixing which brings inorganic nutrients from the deep water up into the surface layer where radiation from the sun makes photosynthesis possible. The amount of post-depositional dissolution varies considerably and depends on the time of exposure of the calcite in the surface layer of the sediment and therefore on the total rate of deposition, and further on an intensity factor. This intensity factor depends on the amount and state of dissociation of the carbon dioxide in the bottom water, and is therefore influenced by the temperature, pressure and past history of the bottom water, and on the production of carbon dioxide by respiration of organisms living in the sediment. The pattern of distribution of calcium carbonate on the ocean floor is thus a complex result of oceanic circulation, depth and temperature distribution, and the interpretation of changes in space and time has to be based on our knowledge of these variables.

Schott (op. cit.) was able to show that in large parts of the Equatorial Atlantic Ocean the Recent sediment stratum is relatively high in calcium carbonate, with foraminifera known to thrive in warm water forming a large part of the fossil assemblage. Below this stratum he found another one much lower in calcium carbonate,

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and with a larger fraction of tests of foraminifera, known to prefer lower surface water temperatures. Schott interpreted this lower layer as laid down during the last glacial age, assuming that the Equatorial surface water temperature was lowered by decreased insolation during this time, and that hence the production rate of foraminifera was decreased. Schott's work, later on extended, (1952) was of basic importance in demonstrating the use of the oceanic sedimentary record for the study of climatic change, and a number of similar studies have since been carried out by other workers (Bramlette, Bradley, 1940; Cushman, Henbest, 1940; Hamilton, 1957; Ovey, 1950; Phleger, 1939, 1942, 1947, 1948; Phleger et al., 1946, 1951, 1953), in the Equatorial Atlantic especially by Ericson (Ericson et al., 1955, 1956). However it appears at the present time uncertain whether the decreased carbonate content in the glacial strata of the Equatorial Atlantic was due to a decrease in the productivity, to an increase in the rate of dissolution depending on the northward flow of Antarctic water along the bottom of the Atlantic Ocean, or to an increased influx of fine grained detrital matter, diluting the pelagic biogenous carbonate in the Atlantic Ocean. Evidence for this latter effect has recently been presented (Broecker et al., 1958).

Another most promising approach to this problem has been made possible by the development by Urey, Lowenstam, Epstein and Mc Kinney (see references in Emiliani, 1955), of a method for determination of the temperature of ocean water from the oxygen isotope ratio in carbonate, laid down in equilibrium with the water. Pioneer studies of paleotemperature distribution in ocean sediments have been carried out by these workers and by Emiliani (op. cit.), the latter employing Atlantic and Caribbean

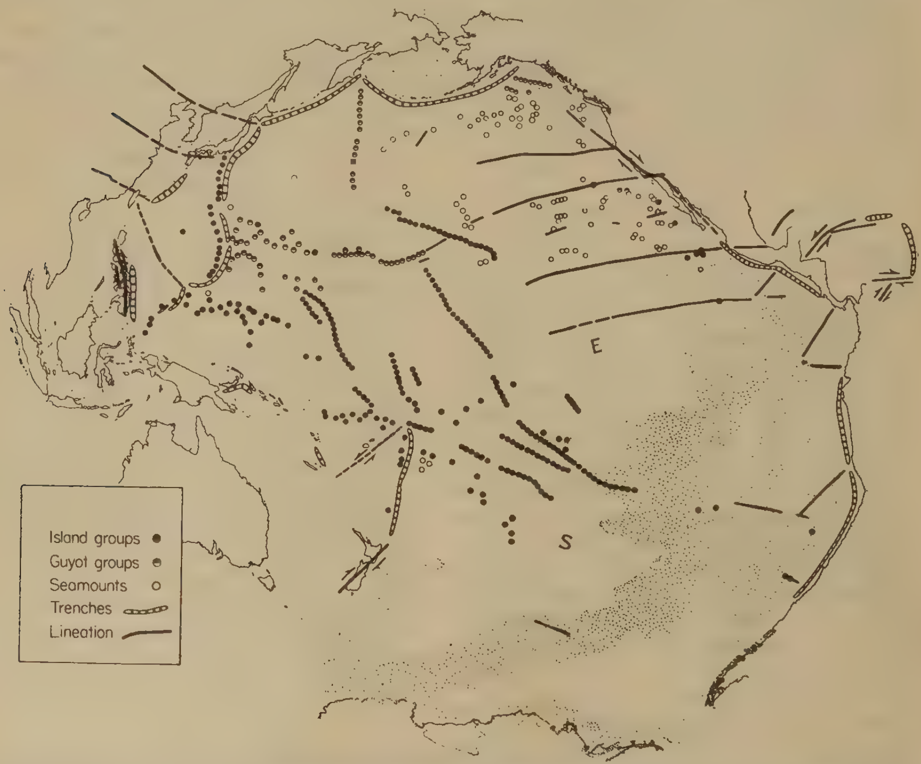

Fig. 1. Structures in the Pacific influencing sedimentation. Stippled area indicates depth less than 4000 m. Two basins appear especially well protected from turbidity inflow from the continents; the East Equatorial Basin, E, and the South Pacific Basin, S. — From Menard and Fisher, J. Geol. *66*, 250, 1958.

sequences of the same type as those used by Schott, but much longer, due to the improved coring technique. Emiliani's investigations confirm in general SCHOTT's and ERICSON's (op. cit.) conclusions regarding the variations in temperature of the surface water based on the frequency of cold and warm water species of foraminifera. Emiliani's record extends back into the Lower or Middle Pleistocene, and includes a series of oscillations of the surface water temperature, as indicated by the oxygen isotope ratios in tests of planktonic foraminifera. Emiliani also reports Washington radiocarbon dates from several levels in the upper part of the sequences. He has further attempted to extrapolate the time scale for this upper part downward in the sequence, and to correlate the temperature oscillations found, with the glacial events recorded on the continents.

2. The sedimentary record below the Equatorial Divergence

The stratification of the Late Tertiary, Pleistocene and Recent sediments has been extensively studied, in the Equatorial Pacific (ARRHENIUS, 1952). This area has been explored in great detail, because the sedimentation basins are located far away from the disturbing influence of the continents, and are surrounded by trenches and rises which prevent inflow of sediments along the bottom (fig. 1). Secondly, there exists in the surface layer of the ocean a wind driven circulation mechanism which controls the production and sedimentation of organic matter, and therefore the biostratigraphy. It appears possible in this area to establish a relationship between the changes in geologic time of trade wind intensity, and simultaneous changes in the composition of the sediment.

The mechanism of sedimentation in the East Equatorial Pacific is schematically illustrated in fig. 2. The central diagram of this figure shows a meridional cross section through the surface layer of the ocean in the East Equatorial Pacific at longitude 120—130° W, where the features of the vertical circulation are well developed, and where the regularity of the sedimentation makes possible a quantitative study of the variations in time of inorganic components.

The temperature distribution is in this middle diagram indicated by the isotherms for 15, 17, 20, 25 and 27° C. The cold, nutrient-rich intermediate water is marked by a dotted surface, and the vertical circulation pattern is shown by arrows. The Equatorial Countercurrent, running eastward, is limited by the South Equatorial Current at about 5° N, and by the North Equatorial Current at about latitude 10° N, both moving in the opposite (westward) direction. Divergence of these wind drift currents produces upwelling along the equator (see discussion in CROMWELL, 1953). The rise of the intermediate water, which is high in nutrient salts, into the surface layer, where most of the sunlight is absorbed, leads to a strongly increased production of algae, sustaining an increased production of higher members of the food chain. At higher tropical latitudes the lack of a mechanism which enriches the euphotic layer, keeps the productivity low.

The rate of production of skeletal calcium carbonate from coccolithophorids and foraminifera is illustrated in the upper diagram, where the full line curve, marked "Pleistocene minimum circulation (interglacial)" corresponds to present time conditions. The abscissa scale is the same as in the middle graph. The inferred rate of dissolution of calcium carbonate before final burial of the fossils is indicated by the curve "Pleistocene minimum production of cold deep water (interglacial)", and shows an increase under the Equatorial productivity maximum, indicating the effect of carbon dioxide produced by the respiration of bottom living animals feeding on the rain of organic detritus.

The resultant rate of accumulation of calcium carbonate corresponds to the ordinate difference between the two curves. At the intersection of these between latitude 7 and 9° N the carbonate accumulation accordingly drops to zero. Siliceous clays cover the bottom of the ocean north of the present loci of this intersection, the carbonate compensation line.

Paleotemperature measurements have been made using the calcium carbonate tests of both benthonic and pelagic foraminifera (EMILIANI, 1955), and the results for the present sediment surface are indicated at the present-time curve in the diagram. The benthonic tests indicate a temperature of about 1° C in good agreement with the directly measured temperature of the bottom water. The planktonic tests, in accordance with the observed temperature distribution in the surface layer, display a gradient, with rising temperature from the Equator to the north (14.8° at the Equator, 15.3° at latitude 2° N and 15.6° C at latitude 7° N). The temperature values obtained from the oxygen distribution would, however, if they represented the habitat

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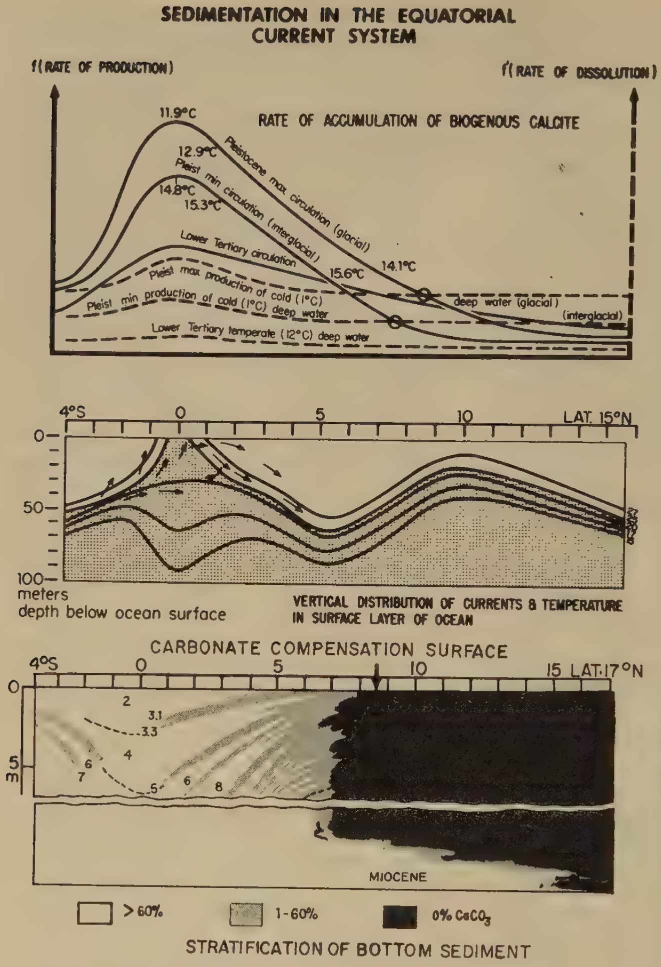

Fig. 2. Meridional profile at approx. long. 130° W. in the Pacific Ocean, showing the distribution of properties in the surface layer of the ocean (middle graph), the stratification of the bottom sediment (lower graph), and the interpretation of the sedimentary record in terms of rates of production, dissolution and accumulation of calcium carbonate from planktonic organisms (upper graph). (From Arrhenius 1959.)

of the foraminifera, place these below the thermocline. If this were the real condition, it is difficult to understand the meridional gradient in temperature, indicated by the isotopic composition of the calcite tests. Although well developed in the surface layer of the ocean, no such gradient is found below the thermocline. As is shown below, the isotopic gradient displayed by the foraminiferal tests exists and is even more marked during past ages (11.9° C at the Equator, 12.9° at latitude 2° N and 14.1° at latitude 7° N, during maximum circulation which occurred during the Riss [Illinoian] Glacial Age). The present conclusion is that the paleotemperature data from planktonic foraminifera show a trend which is in good agreement with the observed surface temperature distribution. The data therefore probably furnish indications of the relative temperature variations with time. However, the absolute values are difficult to reconcile with the actual distribution of water temperature. Investigations of the vertical distribution of the species in question in the surface layer of the ocean and of the relation between the oxygen isotope ratio of the tests on the one hand and the ambient water temperature on the other, appear needed for an interpretation in terms of absolute temperature.

Before the discussion of the other curves in the upper graph, representing the conditions in the past, the lower diagram in fig. 2 will be explained. This diagram is a generalized cross section through the bottom deposits along the same meridian as in the upper graphs. The ordinate has arbitrarily been chosen = 0 for the present sediment surface. The lower, detached half of the graph, showing the stratification of the Middle Tertiary sediments lacks greatly in detail due to the paucity of observations. The vertical scale is, in this case, relative and reference to the zero level is not available.

The distribution of carbonate concentration along the intersection of the profile with the present sediment surface reflects the productivity distribution in the surface layer of the ocean with the superimposed effect of dissolution. From high values below the Equatorial Divergence, the concentration drops toward higher latitudes, and the present northern carbonate compensation line is found between latitude 7 and 9° N.

The profile also demonstrates in a generalized way the marked stratification of the calcareous deposits. Below the surface layer, which is characterized by relatively low carbonate concentrations, lies a stratum (2), high in carbonate, and coinciding in time with the last glaciation in higher latitudes. This stratum is preceded by another low carbonate unit (3) with a small subordinate maximum (3.2, between the subordinate minima 3.1 and 3.3). Below this is a high-carbonate stratum (4) indicating extraordinarily high rates of accumulation of biogenous carbonate and silica. Altogether about nine major carbonate maxima occur in the Pleistocene part of the sequence. The underlying Pliocene sediments are characterized by less variability with time of the carbonate content. The Pliocene-Pleistocene transition is characterized by a rapid drop in the temperature of the bottom water, indicated by the oxygen isotope distribution in benthonic foraminifera (Emiliani, Edwards, 1953), and by a marked change in the fossil assemblages of coccolithophoridae (Bramlette, Riedel, 1954). This transition is shown as a dashed line crossing over the carbonate compensation surface near the break in the profile.

From measurements in the stratum 4 the full line curve marked "Pleistocene maximum circulation (glacial)" in the top diagram and the dashed curve marked "Pleistocene maximum production of cold deep water (glacial)" have been constructed. The productivity appears to have been largely increased, especially in the Equatorial Divergence and probably to some extent also the dissolution due to respiration of benthonic animals, although not enough to counterbalance the greatly increased rate of deposition of calcareous skeletal remains. As a result the overall rate of accumulation of calcium carbonate reaches a maximum during this time. The greatest increase occurs at the equator, where values of the order 3—10 $g \cdot cm^{-2} \cdot millennium^{-1}$ of calcium carbonate are found.

Although the amount of calcium carbonate relative to the inorganic components of the sediment is an analytically convenient measure of the organic productivity, varying with geologic time, it is not the only one. The variations, described above, are closely connected with still more marked changes in the relative amounts of phosphate from fish debris and of opaline silica from diatoms (Arrhenius et al., 1957; Arrhenius, 1959). The diatoms also display characteristic changes in their reproductive cycle (Arrhenius, 1952 chapters 1.5, and 1.9). The original amounts of diatomaceous opal and skeletal apatite are modified to a lesser extent than the calcite by secondary dissolution, and the distribution of silica and phosphate thus gives a still better approximation of the productivity in the past than the distribution of calcium carbonate.

As already mentioned above the paleotemperature data in the top graph indicate a steepening of the temperature gradient away from the Equator, which is taken as additional evidence for an increased rate of upwelling in the divergence as the cause of the increased productivity. The reason for this intensified vertical circulation occurring during the glacial ages is believed to be an increase in the tropical atmospheric circulation depending on a displacement toward the Equator of the high pressure centers now located between latitude 20 and 35°. Under these conditions the stratification of biogenous components in the Equatorial Pacific provides a direct and undisturbed record of the climatic evolution of the Earth during the last few million years. An estimate of the relative variations in trade wind intensity in the past, and a discussion of the time factor on the basis of the sedimentary record is given in the last part of this paper.

Due to the higher production of biogenous calcite and opal in the Equatorial Divergence, the time-rock units are thickest under the Equator, and thin out toward the north and south as is schematically indicated in the lower graph of fig. 2. A detail correlation of the Pleistocene strata has been carried out within the zone of high productivity around the Equator, and with less certainty to the bordering compensation surfaces (Arrhenius, (1952).[1] A stratigraphic subdivision of the Pleistocene clay formation is still lacking, mainly because of the great uniformity of most sections through this formation. The directly underlying Pliocene clay sediments are characterized by a higher and varying manganese and phosphorous content (Arrhenius, 1952, Revelle et al., 1955), and by a lower content of detrital minerals like quartz (Rex, Goldberg 1958), indicating a lower total rate of deposition of detrital minerals in Tertiary than in Quaternary time.

Apparently due to tectonic disturbances of Tertiary age, seamounts and ridges were created in the area in question. Due to their elevation above the sedimentary basins, many of these topographic highs have not received any accumulation of sediment since the time of disturbance. Tertiary sediments of varying age thus outcrop on these highs, and a reconstruction can be made of the sedimentation during the early part of the Cenozoic era. It appears that the northern carbonate compensation line in Lower Tertiary was located much farther north than at present, probably north of latitude 45°. However, it was gradually displaced southward, passed latitude 16° N in Miocene time, and reached its approximate present location in Upper Miocene or Pliocene time. Lower Tertiary conditions are illustrated by the corresponding curves in fig. 2. Oxygen isotope measurements of benthonic foraminifera from these strata indicate bottom water temperatures of approximately 10° C as compared to 1—2° throughout the Pleistocene (Emiliani, 1955; Emiliani, Edwards, 1953). It is believed that the large meridional extent of carbonate sediments in Lower Tertiary time was due to a decreased rate of dissolution rather than to an increased over-all rate of production. This interpretation is supported by the observation of a low relative barium content in the calcareous Tertiary as compared with the Pleistocene sediments below the Equatorial Divergence (Goldberg, Arrhenius, 1958, par. 5.4). Barium is concentrated by marine organisms before or after death, and the barium concentration relative to the inorganic fraction of the sediment is another parameter, indicative of the rate of organic productivity in the surface layer of the ocean (fig. 3).

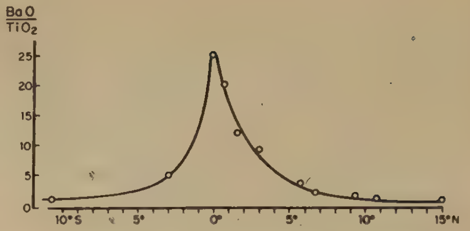

Fig. 3. Relative rate of accumulation of barium as a function of latitude, across the equatorial zone of high organic productivity. The rate is represented by the ratio BaO/TiO_2 in the Postglacial sediments. (From Goldberg, Arrhenius 1958.)

3. The time element

The stratification of the Equatorial calcareous Pleistocene, and the correlation of the strata throughout the Equatorial zone from long. 90° W to long. 180°, makes it possible to compare the variation in space of the content in each time-rock unit of specific fossils, minerals or elements. Such investigations have demonstrated (Arrhenius, 1952) that in the shielded sedimentation basins of the East Equatorial Pacific (fig. 1), the integral of the titanium content from the present surface to any given isochronous level in the Pleistocene strata, is subject to but small variations in space. The titanium content is assumed proportional to the total amount of inorganic matter in the sediment, and the results consequently indicate that in spite of the large variation in thickness of the time-rock units due to varying admixture of biogenous silica and calcium carbonate, the rate of accumulation of non-biogenous matter can, as a first approximation, be regarded as constant in space within the area in question during any given Pleistocene-Recent time interval. Therefore, the relative rate of accumulation over the area of any component during a given time interval can be expressed as the ratio of concentration of the component in question to the concentration of titanium. Such computations form the basis for the curves in the top diagram of fig. 2, expressing the rate of accumulation of carbonate as a function of latitude.

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[1] Near these surfaces the carbonate content has been found to be influenced by postdepositional dissolution and small fluctuations in the location of the compensation line to such an extent that correlation of the strata becomes difficult, unless a large number of sections are available. For this reason the previous correlation of the strata of core 58 near the northern compensation surface can not be trusted in detail.

As has been mentioned above, the Pleistocene formation north of the northern compensation surface consists of a uniform, buff clay with practically no variation in the titanium content above the level of the analytical error (Goldberg, Arrhenius, 1958 par. 5.7). This clay sediment is known to consist of several components with a different mode of formation or transportation. Quantitatively the most important of these components are probably windborne and waterborne detrital minerals and pyroclastics from the continents, and marine hydrogenous minerals. These components are known to differ markedly in their titanium content, and variations of this content by more than a factor of two are observed in sedimentary sequences with large changes in the proportions of the components in question. The uniformity in titanium content and thus, presumably in the relative proportions of inorganic components in the Upper Pleistocene clay sediments in the East Equatorial Basin, may consequently be interpreted in two ways: either the rates of these components varied in such a way that the proportions remained constant, or they did not vary above the limits of detectability. The former alternative appears highly improbable. It is thus concluded that in the area and during the period in question, the rate of accumulation of inorganic components did not vary in a detectable way and this rate is therefore as a first approximation taken as constant (Arrhenius, 1952). This approximation is extended to the adjacent zone of equatorial carbonate sediments as these belong to the same physiographic province (fig. 1).[1]

This implies that a unit mass per surface area of aluminum, titanium, or other element proportional to the total of silicate phases, required approximately the same amount of time for accumulation during different Upper Pleistocene stages, and that the relative rates of accumulation within each time-rock unit can be compared with the rates found in other time-rock units.

This approximation is valid only under the uniform conditions of sedimentation within the basins in question, and cannot be directly applied to other areas of the ocean. Near and on topographic highs and in areas without protection against turbidity flow, the uniformity of sedimentation often appears to be disturbed and age estimates on the basis of the total amount

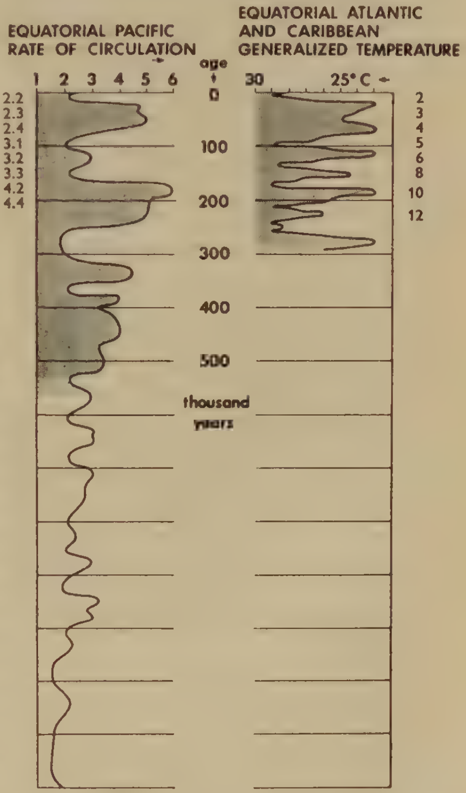

Fig. 4. Left. Relative rate of low latitude atmospheric circulation during the Pleistocene, estimated from the rate of accumulation of biogenous solids below the Equatorial Current System in the Pacific. The time scale is based on the total accumulated amount of titanium calibrated by radiocarbon. The Pliocene-Pleistocene boundary falls within the lowest two sections of the graph. (After Arrhenius 1952.)

(Right.) Atlantic surface water temperature from oxygen isotope data. The extrapolation of the time scale beyond 30,000 years is based on Emiliani's assumption that each climatic cycle had the same duration. (Compiled from Emiliani 1955.)

The numbers in the graphs refer to the stratigraphic subdivisions used in Pacific and in the Atlantic sedimentary sequences.

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[1] For reasons specified in Goldberg, Arrhenius (1958), it is difficult, at the present time, to estimate quantitatively the limit of detectability of variation in the rate of accumulation of one of the inorganic components mentioned. It is believed, however, that a change by a factor of two would be well above this limit.

of any component in a column of unit cross section become uncertain.

Attempts have been made to date the different strata of the Atlantic and Pacific sequences, most of the recent ones using the carbon-14 method. The age information in the Pacific is derived from the measurement of one core carried out by Libby in 1950 (ARRHENIUS, KJELLBERG, LIBBY, 1951). The Atlantic cores are covered by a number of later and more accurate measurements by Suess and Rubin (EMILIANI, 1955).[1] Due to the short halflife of C^{14}, only the very top strata could be measured, corresponding to a few 10,000-year periods. In order to estimate the age of older strata, extrapolation techniques have been used. In the Equatorial Pacific these are based on the observation mentioned above of relative uniformity in space and time of the rate of accumulation of inorganic components. In a column of constant cross section, a given mass of these components under such circumstances corresponds to a definite length of time, which can be determined by calibration with radiocarbon. On this basis, the time-scale for the Pacific events, shown in the left diagram in fig. 4, has been constructed. This chronology can only be regarded as a first approximation, as the error is cumulative. However, it is believed that extrapolations like the present one, and the one made by Emiliani, represent the best estimates of the Pleistocene time-scale available at the present time, with the exception of the last Glaciation, and Postglacial time, where the continental record from high northern latitudes is known with greater precision.

4. The Atlantic record

Emiliani observed that in the Atlantic and Caribbean cores investigated by him, each major temperature cycle corresponds to a sediment layer of relatively constant thickness. This implies that in contrast to the conditions in the Pacific, approximately the same amount of both biogenous calcium carbonate and silica, and non-biogenous components were deposited during each one of the Pleistocene climatic cycles recorded. On the basis of this observation, Emiliani makes the assumption that the cycles all occupy an equal length of time, and that the age of the different strata is directly proportional to their depths below the surface. The estimate of the proportionality factor is based on a number of radiocarbon measurements in the surface layer.

The right-hand diagram in fig. 4 shows in a generalized way the temperature of the surface water from oxygen isotope data as a function of time according to Emiliani's estimate. Comparison with the left-hand graph shows a satisfactory agreement between the Atlantic-Caribbean and the Pacific records for the last 100,000 years, and Emiliani's stages 2, 3 and 4 appear to be isochronous with Arrhenius' stages 2.2, 2.3 and 2.4. Below the 100,000-year level, corresponding to Emiliani's stage 5, and Arrhenius' substage 3.1, it is difficult to attempt a realistic correlation of the strata on the basis of the present time information. If it were assumed that both time-scales were correct, Emiliani's stages 6 and 8 could correspond to substages in Arrhenius' stage 3, which could be better resolved in the Atlantic than in the Pacific, due to the higher rate of deposition of non-biogenous minerals in the Atlantic. Emiliani's stages 10 and 12 could in such a case correspond to 4.2 and 4.4 in the Pacific.

Another possibility, which at the present state of information appears worthwhile considering, is that the assumptions used in the extrapolation systems are such crude approximations that they lead to apparent discrepancies in the ages of corresponding time-rock units in the two oceans when the extrapolation is carried further back in time than 100,000 years. This opinion is shared in part by Emiliani (l.c., p. 561—562) insofar as he suggests that the Atlantic chronology is correct, and the Pacific invalid, and that time scale of the Pacific record should be shrunk by a factor of 1.8. However, the justification of such a modification necessitates substituting the titanium rate value from a core with a high rate of biogenous deposition, and therefore with a relatively good stratigraphic resolution, by a value from a poorly correlated sequence near the northern carbonate compensation surface (see footnote, p. (7). Further, the strata above the 100,000-year level, which appear to correlate well between the Atlantic and Pacific, would be brought out of phase.

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[1] Among his chronological references Emiliani also includes age determinations based on the radium content of the sediment. However the observation of secondary redistribution of radium in the sediment (ARRHENIUS, 1959; ARRHENIUS, GOLDBERG, 1955; KOCZY, 1956; BROECKER et al, 1958) indicate that age determinations based on the distribution of radium are unreliable, unless support of the parent element ionium (Th 230) is proved in each individual case.

In view of the conflicting evidence, it appears desirable at the present time to assign the chronology of Pleistocene strata older than a hundred thousand years to the realm of order of magnitude, pending direct dating of these sediments by their ionium and thorium content, or by other absolute methods. Such attempts are being made at the present time.

REFERENCES

Arrhenius, G., Kjellberg, G., and Libby, W. F., 1951: Age determination of Pacific chalk ooze by radiocarbon and titanium content. *Tellus* **3**, 222—229.

Arrhenius, G., 1952: Sediment cores from the East Equatorial Pacific. *Rep. Swed. Deep Sea Exp.*, **5**.

Arrhenius, G., Bramlette, M. N., and Picciotto, E., 1957: Localization of radioactive and stable heavy nuclides in ocean sediments. *Nature* **180**, 85—86.

Arrhenius, G., 1959: Sedimentation on the ocean floor. *Researches in geochemistry* (ed. Ph. H. Abelson), Wiley, N. Y.

Arrhenius, G., and Goldberg, E., 1955: Distribution of radioactivity in pelagic clays. *Tellus* **7**, 226—231.

Bramlette, M. N., and Bradley, W. H., 1940: Geology and biology of North Atlantic deep-sea cores between Newfoundland and Ireland. *USGS Prof. paper* 196 A. Pt. I.

Bramlette, M. N., and Riedel, W., 1954: Stratigraphic value of discoasters and some other microfossils related to Recent coccolithophores. *Jour. Paleont.* **28**, 385—403.

Broecker, W., Turekian, K., and Heezen, B., 1958: The relation of deep sea sedimentation rates to variations in climate. *Am. J. Sci.* **256**, 503—517.

Cushman, J. A., and Henbest, L. G., 1940: *USGS Prof. paper 196 A.*, Pt. 2.

Cromwell, T., 1953: Circulation in a meridional plane in the Central Equatorial Pacific. *Jour. Mar. Research* **12**, 196—213.

Emiliani, C., 1955: Pleistocene temperatures. *J. Geol.* **63**, 538—377.

Emiliani, C., and Edwards, G., 1953: Tertiary ocean bottom temperatures. *Nature* **171**, 887.

Ericson, D. B., Ewing, M., Heezen, B. C., and Wollin, G., 1955: Sediment deposition in deep Atlantic. *Geol. Soc. Am. Spec.* Paper 62, 205—220.

Ericson, D. B., and Wollin, G., 1956: Correlation of six cores from the Equatorial Atlantic and the Caribbean. *Deep Sea Research* **3**, 104—125.

Goldberg, E., and Arrhenius, G., 1958: Chemistry of Pacific pelagic sediments. *Geochim. Cosmochim. Acta* **13**, 153—212.

Hamilton, E., 1957: Planktonic foraminifera from an Equatorial Pacific core. *Micropaleont.* **3**, 69—73.

Koczy, F., 1956: Vertical eddy diffusion in deep water. *Nature* **178**, 585.

Ovey, C. D., 1950: On the interpretation of climatic variations as revealed by a study of samples from an Equatorial Atlantic deep-sea core. *Roy. Met. Soc.*, Centennial Proc., 211—215.

Phleger, F. B., 1939: Foraminifera of submarine cores from the continental slope. *Geol. Soc. Am. Bull.* **50**, 1395—1422.

Phleger, F. B., 1942: Foraminifera of submarine cores from the continental slope. *Geol. Soc. Am. Bull.* **53**, 1073—1097.

— 1947: Foraminifera of three submarine cores from the Tyrrhenian Sea. *Göteborgs Kungl. Vet. o. Vitterh. Samh. Handl.* 6, ser. B, Bd 5, No. 5.

— 1948: Foraminifera of a submarine core from the Caribbean Sea. *Ibid.* No. 14.

Phleger, F. B., and Hamilton, E. A., 1946: Foraminifera of two submarine cores from the North Atlantic Basin. *Geol. Soc. Am. Bull.* **57**, 951—965.

Phleger, F. B., and Parker, F. C., 1951: Ecology o foraminifera northwest Gulf of Mexico. *Geol. Soc. Am. Mem.* 46.

Phleger, F. B., and Peirson, J. F., 1953: North Atlantic foraminifera. *Rep. Swed. Deep Sea Exp.* 1947—1948, 7.

Revelle, R., Bramlette, M., Arrhenius, G., and Goldberg, E., 1955: Pelagic sediments of the Pacific. *Geol. Soc. Am., Spec. Paper* **62**, 221—236.

Rex, R., and Goldberg, E., 1958: Quartz contents of pelagic sediments from the Pacific Ocean. *Tellus* **10**, 153—159.

Schott, W., 1935. Die Foraminiferen in dem aequatorialen Teil des Altantischen Ozeans. *Wiss. Ergebn. d. Deutsch. Meteor-Exp.* 1925—1927, **3**, T 3.

Schott, W., 1952. On the sequence of deposits in the Equatorial Atlantic Ocean. *Göteborgs Kungl. Vet. o. Vitterh. Samh. Handl.* 6, ser. B, Bd 6, No. 2.

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Photosynthetically Active Accessory Pigments of Cryptomonads

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The Cryptophyceae have attracted interest as a minor algal group of uncertain taxonomic affinities,

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notable for the varied coloration of its pigmented representatives[1]. The isolation into laboratory culture of the red, marine cryptomonad *Rhodomonas lens* by L. Provasoli[2] has prompted studies of the nature and function of its plastid pigments. The results are communicated here in brief, together with those obtained afterwards with the brown-coloured flagellate, *Cryptomonas ovata*. These and the chemical investigations by Allen, McLaughlin and Dougherty and by Ó hEocha and Raftery[3] on a greater variety of species, establish the common occurrence of phycobilin-like pigments within the cryptomonads and their role as accessory photosynthetic pigments.

Cultures of *Rhodomonas lens* Pascher and Ruttner and *Cryptomonas ovata* var. *palustris* Pringsh. were provided by L. Provasoli and Richard Starr, respectively. Both organisms yielded dense cultures after 4–6 weeks when grown in synthetic liquid media (unpublished formulations of L. Provasoli) at 20° C. with continuous illumination of 50–100 ft.-candles intensity. The cells were harvested by continuous-flow centrifugation at 5,000 r.p.m.

Extraction and purification of the water-soluble pigments were carried out in the cold at *p*H 6–7. The cells were ruptured by passage through a needle valve (French press) at 15,000 lb./sq. in., and the homogenate was clarified by centrifugation at 144,000*g* for 1 hr. or more. The pigment of the brilliantly fluorescing supernatant was precipitated with ammonium sulphate, re-dissolved in dilute saline, and chromatographed on tricalcium phosphate, using the method of Swingle and Tiselius[4] and Haxo, Ó hEocha and Norris[5], but omitting diatomaceous earth, which adsorbed a portion of the pigment irreversibly. The fat-soluble pigments residing in the particulate fraction were extracted with methanol at *p*H 8–9 and fractionated by column chromatography on polyethylene powder and conventional adsorbents. Spectral analyses were made with a Beckman *DU* spectrophotometer.

Photosynthetic action spectra of freshly harvested cells were measured polarographically at 20° C. using Haxo and Blinks's method[6]. The reaction vessel was modified, however, by recessing the platinum electrode to accommodate a 0·25-mm. layer of suspended cells, horizontally oriented in the beam from the monochromator.

The spectral similarity of centrifuged aqueous extracts of *R. lens* to C-phycoerythrin was noted earlier by Wolken and Haxo (cf. L. Provasoli, ref. 2). On chromatographic columns several diffusely adsorbed pink zones were observed, all of which gave

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similar spectra. The principal fraction, eluted with 0·1 *M* phosphate buffer, had the following characteristics: maximal absorption at 545 mμ and secondary peaks at 390 and 275 mμ; strong yellow fluorescence; non-dialysable; precipitation from aqueous extracts upon heating, by addition of three volumes of acetone, and by saturated ammonium sulphate at 0° C.; photolability moderate at 20° C., slight at 5° C.

Chromatographically purified pigment from *C. ovata* showed similar solubility properties, but displayed a reddish-orange fluorescence and absorption peaks at 568 and 285 mμ. The pigments of the two cryptomonads are therefore spectrally distinct. Their observed properties suggest that they are bilichromoproteins similar to, but not identical with, the single-peaked C- and B-phycoerythrins[7,8]. Their spectral properties and possibly also their precipitation only at high ammonium sulphate concentrations are features which distinguish them from the known bilichromoproteins of red and blue-green algae.

Both cryptomonads yielded three chlorophyll fractions (absorption maxima in ether): chlorophyll

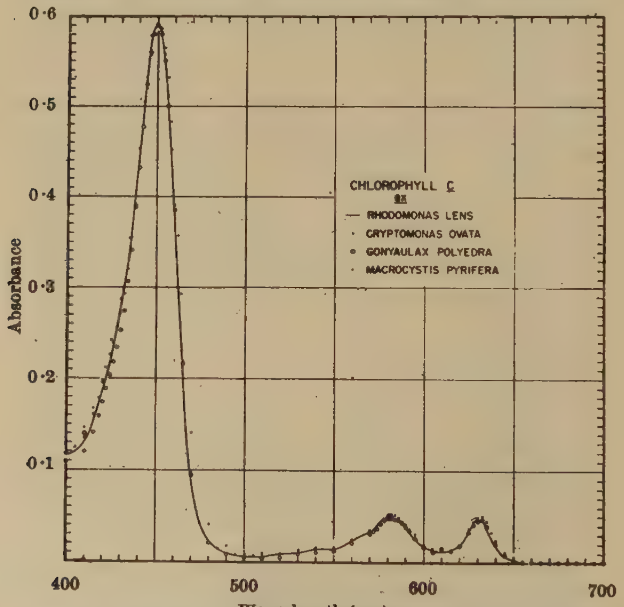

Fig. 1. Absorption spectra in ethyl ether of chlorophyll *c* from *Rhodomonas lens*, *Cryptomonas ovata*, *Gonyaulax polyedra* and *Macrocystis pyrifera*

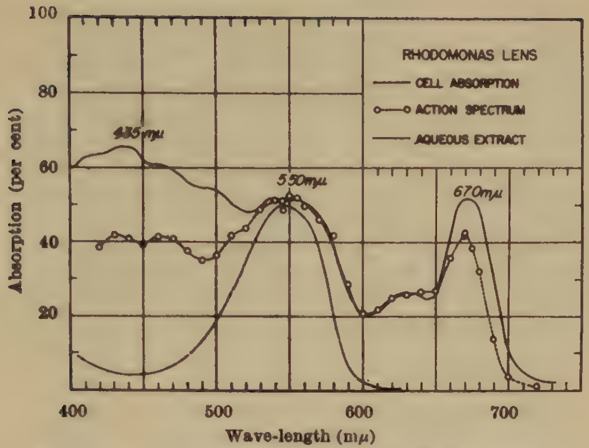

Fig. 2. Photosynthetic action spectrum of *Rhodomonas lens* and absorption spectra of the intact cells and of the aqueous extract

a (*665*, 615, 577, 530, *430*, *410* mμ) ; chlorophyll *c* (*633*, 581, *450* mμ) ; and an unidentified hypophasic component (*667·5*, 615, 576, 531, 500, 429, *412* mμ). The latter may be a degradation product of chlorophyll *a*, but it was not observed in similarly treated extracts of a dinoflagellate (*Gonyaulax polyedra*) or of brown algae (*Eisenia arborea* and *Macrocystis pyrifera*). The solubility and adsorption properties, and in particular the spectral properties (Fig. 1) of the chlorophyll *c* from *R. lens* and *C. ovata*, corresponded closely with our preparations of this pigment from the above-named reference sources. Evidence for the presence of chlorophyll *c* in *C. ovata* was recently obtained by French, Elliott and Allen (ref. 9 and personal communication) from absorption spectra of intact cells.

The carotenoid hydrocarbons of *C. ovata* included, as the major component, α-carotene (identity confirmed by co-chromatography with an authentic sample) and a less strongly adsorbed polyene (absorption maxima in hexane at 471, 442 and 418 mμ), probably ε-carotene. The xanthophylls of *C. ovata* were more abundant than the carotenes (ratio 2·4 : 1). The absorption spectrum and the partition behaviour of the principal xanthophyll corresponded closely to those of zeaxanthin ; however, identity with the very similar pigment diatoxanthin was not precluded. The poly-oxy carotenoids, peridinin and fucoxanthin, were not present in detectable amounts in extracts from either cryptomonad, although these pigments were readily isolated by the same procedures from reference sources. A similar role for phycocyanin in

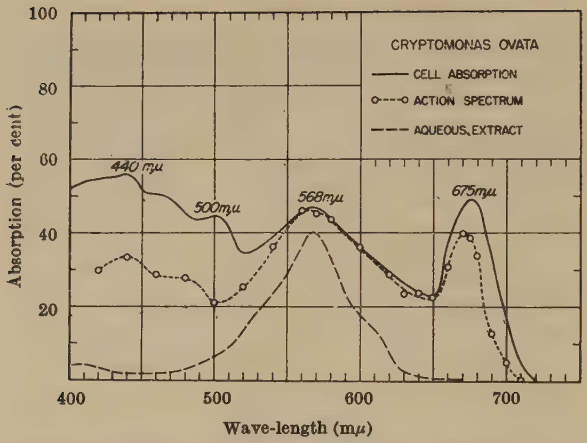

Fig. 3. Photosynthetic action spectrum of *Cryptomonas ovata* and absorption spectra of the intact cells and of the aqueous extract

the photosynthesis of cryptomonads has subsequently been established in the case of *Hemiselmis virescens*, which contains abundant amounts of an aberrant phycocyanin accompanied by chlorophylls *a* and *c*.

That the 'phycoerythrins' of both flagellates are effective sensitizers in photosynthesis is demonstrated by the photosynthetic action spectra and corresponding absorption spectra presented in Figs. 2 and 3. Photosynthetic activity is highest in the middle of the spectrum (540–570 mμ) where the water-soluble pigments contribute most prominently to cell absorption. A somewhat lower effectiveness for light absorbed by chlorophyll is indicated. This situation is seen most clearly at wave-lengths beyond 660 mμ, where absorption may be attributed solely to chlorophyll.

Previous work on the bilichromoproteins has been concerned mainly with those of red and blue-green algae, in which they function as accessory pigments to chlorophyll *a* alone[10]. In the former group of algae, small amounts of chlorophyll *d* may also be present. The cryptomonads now examined differ from other types of algae bearing phycobilin in that photosynthetically active bilichromoproteins are associated with chlorophyll *c* as well as chlorophyll *a*. It is noteworthy in this connexion that the 'inactive chlorophyll' fraction of cryptomonads is small relative to that characteristically encountered in the Rhodophyta[6].

The evolutionary relationships of the cryptomonads remain unsettled, although Pascher[11] proposed that they are related to the dinoflagellates. In this connexion, it is of interest to compare the plastid pigments of the cryptomonads and the dinoflagellates. Both groups contain chlorophylls *a* and *c*, but these two chlorophylls also occur in diatoms and in the brown algae. Peridinin, the characteristic carotenoid of dinoflagellates, was not detected in the cryptomonads that we have examined. In further contrast, bilichromoproteins have not been detected in the dinoflagellates, although species with blue chromatophores[12] have not been examined in this respect. Available information, although limited, suggests that the cryptomonads possess a distinctive complement of plastic pigments.

We are indebted to Nao Belser and William McClure for their assistance in certain phases of this study.

[1] Fritsch, F. E., "The Structure and Reproduction of the Algae", 1 (Camb. Univ. Press, 1956).

[2] Provasoli, L., *Boll. Zool. Agrar.*, **22**, 143 (1956).

[3] See accompanying communications: Allen, Mary Belle, Dougherty, E. C., and McLaughlin, J. J. A., and Ó hEocha, C., and Raftery, M.

[4] Swingle, S. M., and Tiselius, A., *Biochem. J.*, **48**, 171 (1951).

[5] Haxo, F. T., Ó hEocha, C., and Norris, Phyllis, *Arch. Biochem. Biophys.*, **54**, 162 (1955).

[6] Haxo, F. T., and Blinks, L. R., *J. Gen. Physiol.*, **33**, 171 (1950).

[7] Ó hEocha, C., *Arch. Biochem. Biophys.*, **73**, 207 (1958).

[8] Airth, R. L., and Blinks, L. R., *Biol. Bull.*, **111**, 321 (1956).

[9] French, C. S., and Elliott, Ruth F., Carnegie Institution of Washington, Year Book 57, p. 282 (The Lord Baltimore Press, Inc., Baltimore, Maryland, 1958).

[10] Blinks, L. R., "Ann. Rev. Plant. Phys.", **5**, 93 (1954).

[11] Pascher, A., *Ber. deutsch. Bot. Ges.*, **29**, 193 (1911).

[12] Geitler, L., *Rev. Algol.*, **1**, 357 (1924).

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SCRIPPS ESTATES SITE I (SDi-525); A PRELIMINARY REPORT ON AN EARLY SITE ON THE SAN DIEGO COAST

Introduction

The existence of the Scripps Estates Site I has been known for decades, but virtually nothing has been published concerning it. Early archaeological work was done by Malcolm J. Rogers of the San Diego Museum of Man in the late 1930's and during World War II as burials became exposed during the removal of top soil and the construction of military fortifications. The importance of the site was brought to the attention of the authors in December, 1958 when Dr. George Shumway uncovered a burial while digging in his front lawn. Dr. Shumway proceeded to excavate this burial in a scientific manner and in so doing discovered several more burials. The composition of the deposit in which the burials occurred, as well as the artifacts recovered suggested that the site might be of considerable antiquity. A subsequent series of 3 radiocarbon dates from the site has substantiated the antiquity of this site.

Carbon -14 dates of 5500, 6700 and 7400 B. P. and the paucity of published material on early coastal sites in San Diego County makes the Scripps Estates Site I a site of considerable significance in southern California archaeology.

The University of California Archaeological Survey, Los Angeles, undertook excavations on the lot adjacent to the home of Dr. George Shumway in 1959. Dr. John Isaacs, the owner of the lot gave his full cooperation. Excavations were done between semesters and on two week ends. Although the Survey collected a fairly representative artifact assemblage, and excavated three burials, it was clear that a larger sample was desirable. Dr. George Shumway, with the help of James Moriarty and friends continued excavation after the UCLA crew left the field, and as a result they have supplied the needed information. Dr. Shumway has described the location and geology of the site and worked with James Moriarty on the report of their archaeological material. Claude Warren has discussed the material recovered by the UCLA crew. Two additional papers are forthcoming; a report on the skeletal material by James Moriarty and an analysis of shell samples by Dr. Carl Hubbs.

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LOCATION, TOPOGRAPHIC AND GEOLOGIC SETTING, AND SOIL PROFILE

Site Location

Scripps Estates Site I (SDi-525) is located in western San Diego County, California, at a latitude of approximately 32°52'22" N. It lies at the seaward edge of the mesa-complex which further inland is called Kearney Mesa and Linda Vista Mesa. This mesa-complex is dissected by numerous canyons and valleys. Three of these, Soledad Valley, Hidden Valley, and Rose Canyon, together with sea cliffs on the west, practically isolate a portion of the mesa surface, called Torrey Pines Mesa. The elevation of the surface of Torrey Pines Mesa generally is between 110 and 120 m. Small canyons cut the western edge of Torrey Pines Mesa, and it is along the south rim of one of these, Sumner Canyon, that Scripps Estates Site I is located. The site is about 2.9 km. north of Alligator Point and about 0.9 km. north of the Scripps Institution of Oceanography.

The site lies within the subdivision Scripps Estates Associates, Inc., and takes its name from the subdivision. The midden is found mainly on lots 14 through 20, which front on Ellentown Road, but the site apparently extends south of the road also. The San Diego Museum of Man site number is SDM-9-W. Carter (1958, p. 214) mentions it under the name of Scripps Faculty Site.

Torrey Pines Mesa holds a complex of archaeological sites. Eight canyons roughly comparable with Sumner Canyon are found along the western edge of Torrey Pines Mesa, separated by distances of less than 1 km.

On the mesa surface the distance between canyon rims is about one half a kilometer. Sites are found along the rims of a number of these canyons (for locations, see Map 1), and in places the sites may have been continuous from one canyon rim to the next. Archaeological material similar to that at Scripps Estates Site I occurs along the north rim of Sumner Canyon and a site is more or less continuous from there to the south rim of Callan Canyon. Southeast of Site I at a distance of about 0.3 km., and on the opposite side of La Jolla Shores Drive from Site I, lies an extensive site which has not yet been studied (Map 2). For purposes of discussion this is called Site II. Originally it may have been contiguous with Site I.

Geomorphic and Geologic Setting

The elevated block which constitutes Torrey Pines Mesa is composed mainly of Eocene sandstones (Hanna, 1926). In the region of Sumner Canyon and Callan Canyon only the Middle Eocene Rose Canyon Formation is present, consisting of interbedded sandstone, shale, and conglomerate. Farther north, the Torrey Sand of Lower or Middle Eocene age, and the Del Mar Sand of Lower Eocene age are present. A basalt dike is exposed on the beach about 0.6 km. south of the mouth of Sumner Canyon.

Conglomerate lenses are exposed on the sea cliffs in the vicinity of Sumner Canyon and Callan Canyon. These conglomerates are made up chiefly of red rhyolites, but other volcanics and crystalline rocks are present also. Boulders and cobbles from these conglomerates weather loose and collect at the foot of the sea cliff, together with boulders and cobbles from other sources. They also pave the wave-cut terrace which underlies the beach sand. This cobble pavement often is exposed in winter seasons when beach sands are removed by winter wave action. Thus an ample source of cobbles is present now, and undoubtedly was present in the past, from which manos, hammerstones, scrapers, and other implements could be made. Large slabs of sandstone, from which metates could be fashioned, are found abundantly along the beach.

The surface of Torrey Pines Mesa and the Kearney Mesa - Linda Vista Mesa complex were cut late in the Tertiary Period. Sand ridges of the Plio-Pleistocene Sweitzer Formation are found on the mesa surface. One of these ridges lies east of the site at a distance of about 0.6 km. and has its top about 25 m. higher than the elevation of the site. A prominent feature of these sand ridges is the abundance of ironstone concretions about 1 cm. in diameter contained in them (Emery, 1950). These concretions are found in the soil of the site, and their presence there may be due to their down-slope migration from the Sweitzer Sand ridge.

Soil Profile

In spite of the fact that the Site I midden occurs on a topographic rise, it has been a region of soil accumulation during the time of occupation and in the time since then. Shrubs have grown in abundance over the site in historic times and presumably their presence extends back to the time of occupation. These shrubs have caught sand and silt blown to them from the region immediately west of the site by the prevailing westerly winds. The midden owes its preservation to these eolian sediments and to the additional protection offered by the dense growth of shrubbery. According to M. J. Rogers (personal communication), before the removal of topsoil from the southern part of the site during World War II, the shrubs extended into the area south of Ellentown Road. The shrubs now growing on the site are mainly Rhus integrifolia, with Heteromeles arbutifolia present in secondary abundance.

Typical soil profiles are shown by the trench profiles given in Figures 1-3. Due to the removal of the upper soil from much of the site during World War II, complete profiles of the soil are available only at the south edge of the shrubbery as it exists today.

The lowest zone of the soil profile, designated C, is the Eocene sandstone which underlies the site and which outcrops in places throughout the site. In the vicinity of the site the sandstone is uniform in appearance, with grains of medium sand size.

Overlying the bedrock is a well-developed B zone where clay and iron salts have accumulated. The upper 5 or 10 cm of this zone are particularly rich in clay, hence the top of the B zone is distinct. Intermixed with the clay are concentrations of sand cemented with a ferruginous cement. Also found in this B zone are ironstone concretions of the type found on the Sweitzer sand ridges. It is by no means evident that these concretions were not formed in place rather than having been introduced to the site after weathering out of the Sweitzer deposits. The concretions are found throughout the whole soil profile, however, so both origins may have been in effect.

Yellow sand derived from the local sandstone and designated zone A_3 lies above the clay. A caliche cement is present in this zone, and in the overlying A_2 zone, which binds the sand into a rock-like mass when dry, but which has little binding effect when wet. Ironstone concretions are present in this zone, but their concentration is low. Midden shell, bones, and artifacts are present in this zone. The yellow sand is overlain by a dark, caliche-cemented soil, designated zone A_2. Generally the transition from yellow to dark soil is gradational, with a mottled appearance. The mottled effect is due to root holes and other holes which have allowed the darker soil from above to move downward. More rarely there is a distinct caliche layer separating the yellow sand from the darker sand above.

Proceeding upward through the dark soil, zones A_2 and A_1, the caliche cement diminishes and the amount of organic matter in the soil increases. Midden shell is most concentrated in the A_2 zone, and the abundance of it in the A_1 zone decreases upward. The presence of midden shell and artifacts in the upper part of zone A_1 is in small amount, and probably it is there as a result of working of the lower levels by root action and rodent action, for the upper part of this zone probably was deposited by wind action after the time of chief occupation of the midden.

An outstanding feature of the soil profile is the caliche, which is dispersed throughout the soil, and also is present as discrete layers, and as coverings on artifacts, bones, and scattered pieces of rock. The most prominent caliche layer is one which parallels the general ground level within the A_2 zone. With the A_1 zone missing from much of the site, this prominent caliche layer is found only about 10 cm. below ground level. It cuts through burials and definitely was formed later than the burials. Probably this caliche layer is related to the present ground level or to the ground level prior to the removal of the A_1 zone.

A layer of caliche 2 to 3 mm. thick was present around the skull of burial 3, which lay in the A_2 zone. A brief analysis of this material was made by David R. Schink at the Scripps Institution of Oceanography. An X-ray diffractometer run showed pronounced calcite peaks, with secondary quartz and feldspar peaks. Sixty-seven per cent by weight of the caliche was soluble in 2 molar hydrochloric acid, and presumably this soluble portion is mainly calcite.

Rock fragments are present throughout the soil profile. Some of these are pieces of the Eocene sandstone country rock. Most of the pieces are volcanics, metamorphics, or crystalline rocks, and many of these have freshly broken surfaces. These fragments most likely are part of the midden deposit and were carried to the site by man.

George Shumway
2504 Ellentown Road
La Jolla, California

EXCAVATIONS: SHUMWAY PROPERTY

At twilight on 12 December, 1958, the junior writer was spading up lawn in his front yard and struck the skull of what herein is numbered burial 7. The senior writer was notified, and trenching began the next day. It soon was revealed that burial 6 had been struck also in the lawn spading. The trend of these two burials, the presence of a fence to the north of them, and the desire to provide drainage in case of rain prior to removal of the skeletons, determined that the trench should be extended to the southwest, where burials 5 and 8 were discovered later. The tops of burials 6 and 7 were within 25 cm. of the surface of the lawn. In the development of the lawn the soil had been disturbed to a depth of about 10 cm. No grading was done at this location prior to planting of the lawn. Skeleton 6 was buried in an atypical position, so that the upper part of the spinal column was vertical. The skull from this burial was missing; its position would have placed it at about the level of the present lawn and its roots. Possibly it was demolished during the preparation of the lawn, and possibly it lay near ground level for years prior to the lawn planting and disintegrated in the loose upper soil.

Additional trenches were put in by Warren (designated as U.C.L.A. on Map 4) and by the writers (designated by S-M on Map 4). A total of 16 burials were located in this work. In addition, many isolated bone fragments were found. A fragment of a child's jaw was found about 1 m. northwest of burial 8, and half of an adult's jaw was found 2 m. north of burial 6.

A transit survey was carried out during the digging which accounted for the work of Warren and that of the writers as a unit.

Seven burials are being preserved in situ as permanent exhibits. Four of these burials fall entirely on the property of the junior writer (Scripps Estates Associates Lot 16) and the other three fall on the west boundary line of the property (where it joins Scripps Estates Associates Lot 17, owned by Professor J. D. Isaacs). Concrete boxes with walls 10 to 15 cm thick were poured around the burials and waterproof lids attached.

Previous Work at the Site

During the early part of World War II (1940-43) topsoil was removed from a part of the site for the construction of nearby Camp Callan. Malcolm J. Rogers, at that time Director of the San Diego Museum of Man, was present for salvage work on the burials as they came to light during the topsoil removal. Burials were located and leveled by transit, and the salvaged material stored in the Museum for future study. It is unfortunate that a report was not prepared from this salvaged material, for after Rogers left the Museum in 1945, the material was improperly cared for, so that at the present time almost none of it can be located for study. Fortunately, Roger's transit survey data are available, and Rogers has been kind in allowing his data on burial locations to be published in this report together with the locations of the recently discovered burials (Map 3).

It should be noted that Rogers used a sandstone outcrop on Scripps Estates Associates Lot 17 as a reference bench mark for his survey work, and that this subsequently has eroded away. Rogers accompanied the writers to the site and picked out a spot which he estimated to be within 2 or 3 meters of the original spot. This was used in preparing the location figure.

It is probable that a considerable number of artifacts were removed from the surface of the site during the 1930's and perhaps even earlier. During World War II other material was taken by military personnel as gun emplacements were made and topsoil removed. Additional material has been taken since then.

In 1953 road grading for the Scripps Estates Associates subdivision took place. A cut of about two meters depth was taken for the construction of Ellentown Road, and in the loosened soil the senior writer found remnants of two burials. Both burials were rather severely disturbed. A few bones were salvaged, and from these a few measurements were obtained. A portion of one burial was found in place, and in this approximately two dozen beads made from shell were collected. These beads were constructed from the thick part of a heavy shell. Each was spherical in shape, with a diameter of about 5 mm, and had a well-centered drilled hole. The beads were remarkably consistent in shape and size.

In the same year the senior writer made a reconnaissance of the undisturbed areas of the site. A number of manos and 4 or 5 fragments of broken sandstone metates were found. Shell material appeared in abundance on the surface, and it was noted that very little food bone material accompanied the shell. That which did appear was primarily fish. The recognizable lower jaw of the sheepshead and fish vertebrae were the most prominent.

Among the miscellaneous rock pieces found at this time were a group of sandstone balls of high sphericity, with diameters of 10 to 15 cm. A total of eight were found. The high sphericity of these balls, and their presence in number at the site, suggests that they are artifacts, although their use is unknown.

Burial Descriptions

Ten of the recently discovered burials still are in the ground at this time, and seven of these are being preserved in situ. Excavation is incomplete on these ten skeletons, hence only preliminary field measurements are possible on the bones. Brief descriptions of 11 burials are given in Table I; descriptions of the other 5 burials are presented in the following paper by Warren. Field measurements of the skeletal material as it presently exists have been made, but are not presented here because more complete excavation of the burials will yield a better set of measurements.

All of the burials found in place in this site are in flexed position. This statement holds for the burials discovered earlier by Rogers (personal communication) as well as for the more recent discoveries. There may or may not be significance to the azimuthal orientation of the axis of the body in these burials. On a statistical basis the head is toward the north, but this is not always the case. This tendency of the head to be toward the north has been found for other burials identified as La Jollan.

Midden shell is found around the burials and in the space between bones as well as in the surrounding ground. In no case with the 16 recently discovered burials was there a noticeable change in soil around the burial which would

Table 1 - Burial Descriptions

Burial	Skull Depth, cm	Sex	Age	Burial Position	Skeletal Condition	Measurable Skeletal Material	Remarks
1	12	Undet.	Adult	Flexed, on rt. side (?)	Very poor	None	Section of upper portion of skull, part of parietal and frontal, 2/3 portion right zygomatic arch. Metate over skull. (Plate 7b,c)
2	22	Undet.	Adult	Unknown	Poor	Left femur	Left femur, badly fragmented tibia and fibula, a section of two thoracic vertebrae, and a piece of jaw were only pieces recovered.
3	25	Male	Adult	Flexed, on rt. side	Good. Nearly complete except for small bones of hands and feet. Long bones articulated including knee cap.	Almost all	One of the most complete and undisturbed burials of the group (see Plate 8A). Excavation incomplete.
4	6	Undet.	Adult	Flexed, on rt. side	Skull good, skeleton nearly complete.	Skull, possibly other parts	Excavation incomplete.
5	21	Undet.	Child	Flexed, on left side.	Fair. Skull and long bones of right side remain	Skull, femur	Teeth unground, showing little wear. Excavation incomplete.
6	22	Undet.	Adult	Flexed, but not lying on side. Spinal column is down with upper part nearly vertical.	Fair. Skull missing as well as atlas and axis. Long bones poor.	Tibia and fibula	

(Table 1 - continued)

Burial	Skull Depth, cm	Sex	Age	Burial Position	Skeletal Condition	Measurable Skeletal Material	Remarks
7	20	Male	Adult	Flexed, on right side.	Skull good but deformed. Long bones and small foot bones present and partially articulated.	Radius, femur, tibia, fibula	Teeth show only moderate grinding. Shell bead necklace in place with bones. Large shell (*Laevicardium elatum*) close to skeleton.
8	18	Undet.	Child	Flexed, on left side.	Poor. Long bones fragmented, with badly deformed pelvis. Skull much deformed.	None	Large cobble and scraper-like flake with burial.
9 thru 12 (See following paper)							
13	20	Female	Adult	Flexed, on right side.	Fair. Skull badly crushed, with lower jaw and front missing	None without reconstruction	See Plate 8b
14	23	Undet.	Adult	Unknown	Unknown	Unknown	This burial underlies burial 3 and is unexcavated.
15	20	Undet.	Adult	Flexed, on right side.	Fair	Unknown	Underlies a metate. Excavation incomplete. (Plate 8c)
16	23	Undet.	Adult	Flexed, on right side.	Good.	Unknown	Excavation incomplete.

indicate the limits of the hole in which the body originally was placed.

Metates were found in place overlying burials 1 and 15. The burial 1 metate is described in detail by Warren in the following paper. The burial 15 metate was broken in the middle, with one half turned over. It lay over the central part of the body. A group of about 6 pieces of rock were found between 10 and 20 cm. above the metate. These appear to have been placed as a grave marker.

Artifacts

Manos are found in abundance at the site. A total of 55 have been collected by the writers (Plate 1, A). Most of these were collected from the surface over a period of years, but some were found in place. Additional manos were collected by Warren and by Hubbs. It would be difficult to estimate the number that have been removed from the site by others, but it must be considerable. The manos are rather undistinguished in shape, for they were made from water-worn cobbles. They are of a size suitable for use with one hand. Typical dimensions are: length 15 cm; width 10 cm; thickness 6 cm. Most of the manos exhibit two grinding surfaces, but some have only one. Some grinding surfaces show "pecking," i.e., artificial roughening to produce a better grinding surface.

Sandstone metates were discovered with burials 1 and 15. In both cases they were placed directly over the burial and were in close contact with some of the skeletal material. The metate with burial 15 (Plate 8) was essentially worn out when placed in the burial. Its length is 56 cm, its width 36 cm, the maximum thickness is 15 cm, and the minimum thickness at the bottom of the bowl is about 1 cm. A number of broken metate fragments were picked up on the surface of the site, and a few pieces were found in place in the upper soil. One fragment was found with the small pile of rocks which lay above the burial 15 metate. All of the metate fragments were sandstone with one exception, and this was a granitic rock.

Quantities of irregular shaped rock fragments were found scattered through the soil of the site and many additional pieces were present on the surface. A small fraction of these rocks are rounded, water-worn pebbles and small cobbles. The majority of them are chips and broken pieces of cobbles. Some are unmistakably recognized as artifacts, and these might be grouped in two categories, scrapers and hammerstones (Plate 1, C). Considerations of the geological setting of the site lead to the conclusion that nearly all of the rocks and pebbles found there probably were carried to the site for use as tools.

The pieces which with some certainty can be called scrapers are nearly all percussion flaked. Some exhibit sharp edges with major flakes taken from both sides and no evidence of use. Others show secondary flaking as a result of use or resharpening. One particularly fine green felsite scraper showing secondary flaking on all sides was found about 2 m. north of burial 6 at a depth of about 20 cm. Some scrapers (or cutting tools) are made from a large rounded pebble or small cobble. These have on one side the smooth surface original surface of the cobble, and on the other a cutting edge flaked on both sides.

The hammerstones are cobble pieces which have one smooth original side and one side showing considerable chipping, apparently from pounding.

Both the scrapers and hammerstones are made chiefly from fine-grained igneous rocks and porphyries, although quartzite apparently was used also.

The most singular artifact discovered in the site was a shell bead necklace (Place 1 B). This necklace, which occurred with burial 7, is complete, and contained about 90 beads. A few additional beads were found with burials 8 and 13. The beads consisted of selected specimens of the gastropod *Olivella biplicata* which had had the apical end ground off to facilitate stringing. In addition to the 90 *Olivella* beads of the burial 7 necklace, a central pendant bead was found. This is a disc about 3 cm. in diameter and 1 cm thick, probably made from the thick part of the shell of *Tivela stultorum*, the pismo clam. The bead has a biconical central hole.

At a distance of less than 20 cm. from burial 7 a single specimen of the clam *Laevicardium elatum* was found. This specimen was in complete and good condition, and measured 14.5 cm in length and 13.2 cm maximum width. No other specimen of this clam has been found in the midden shell and it seems probable that it was a part of burial 7. Evidence of this clam has appeared only rarely at other midden sites in the San Diego region.

At present this clam is found along the western coast of Baja California as well as in the mud flats in the Gulf of California. Shells without living organisms have been dredged from San Diego Bay (Carl Hubbs, Personal Communication), but apparently it is not presently found in the San Diego region. This suggests that the clam may have ranged further north at the time of the midden or possibly that it represents trade material.

Carbon-14 Dates

Three Carbon-14 dates have been obtained from the site. All of these were made on shells of the California mussel, *Mytilus californianus*. Dating was done at the Scripps Institution of Oceanography through Professor Carl Hubbs by Dr. George Bien and Professor Hans E. Suess.

A date of 6,700 ± 300 years B. P. was obtained for shell taken in the immediate vicinity of burial 7 at a level comparable with that of the skeleton, i.e., in the lower portion of the midden.

Two additional dates were obtained by Professor Hubbs from shell collected in his back yard which lies along the southern edge of the midden. Shell collected at the surface dated 5,500 - 5,600 years B. P. (LJ110). Shell collected at the lowest level of the midden dated 7,470 - 7,500 years B. P. (LJ109).

Other Carbon-14 dates of shell material are of comparable age. Tuthill (Crane and Griffin, 1958) obtained a date of 6,950 ± 350 years B. P. for a midden in Sorrento Valley (Map 1). This site is SDM-W316 in the San Diego Museum of Man numbering system.

A date of 7,300 ± 300 years B. P. has been obtained by the San Diego Museum of Man for site SDM-W45, located on the northern edge of the San Dieguito river valley (Map 1).

Discussion

From the abundance and size of middens along the Southern California coast and the similarity of age of the few that have been dated, it may be assumed that a considerable coastal population existed as long as 7,000 years ago. Most of the middens of the San Diego area exhibit the same crude culture that is found at Scripps Estates Site I, with pressure-flaked projectile points being extremely rare and pottery notably absent. The evidence suggests the hypothesis that for a period of a few thousand years, say between 7,500 and 4,500 years B. P., shell midden makers were abundant, but that in the past few thousand years this shell midden activity diminished to minor importance. From considerations of the diet of the midden people, as revealed at Scripps Estates Site I, and the postglacial history of the earth, a possible explanation for this change in midden-making activity is suggested.

The primary source of food for the shell midden people was the sea. The size of the shell middens and their abundance leaves little doubt of this. Pelecypod shells, chiefly the California mussel, Mytilus californianus, and the scallop Pecten circularis are found in greatest abundance in Scripps Estates Site I. Many other shells and calcareous remains appear in lesser abundance, including abalone, limpet, chiton, sea urchin, and a variety of small gastropods. Fish remains are present in minor amount, but because of the relative ease of decomposition of fish remains compared with shell, fish may have been more important to the diet than the evidence indicates. Artifacts of the fishing industry, such as hooks and net sinkers were not found at the site, however, so perhaps fish were of only minor importance.

The abundant metates and manos in the site suggest that vegetable matter also was important to the diet. There is a high probability that the climate during the time of midden occupation was at least different from what it is today (rainfall 10 to 20 cm/year), and a good possibility that it was more favorable for the growth of plants. Pines and oaks were more abundant in the San Diego region even in historic times than they are at present. The historic Diegueno Indians made use of these plants, and others (Kroeber, 1953; Harding, 1951).

The general diet of the midden people must have been ample and reasonably well balanced. Robert K. Murphy, M.D., studied the skeletal material from Scripps Estates Site I for evidences of pathology and could find no indication of dietary deficiency. Some dental caries appear in the adult specimens and there are indications of arthritic lesions on adult femurs in burials 13 and 3.

The concept of a considerably lowered sea level at the time of Wisconsin glaciation is supported by so many lines of evidence in fields such as glaciology, geomorphology, sedimentation, and marine geology, that for the following discussion it may be accepted as a condition which did exist. A rise in sea level occurred as the glaciers waned, and apparently this was rather rapid at first compared with the more gradual rise that has taken place over the past few thousand years.

A picture of this Holocene transgression was obtained in a recent study by Curray (1959) by obtaining Carbon-14 dates on shells of shallow-water origin found at various depths on the continental shelf west of 93° W. Longitude in the Gulf of Mexico. Presumably these organisms lived in shallow waters during the transgression, and their remains were left behind as the shoreline advanced. Curray's figures are reproduced here (Fig. 4), with his permission, to point out that just prior to the period of shell midden making along the San Diego coast there was a rapid rise of sea level. The importance of the rapid rise of sea level is that it may have provided particularly favorable conditions for the development of shallow-water organisms, and therefore particularly favorable conditions for the development of the midden makers.

During the times of glacially-lowered sea level the mesa surfaces of the San Diego region were dissected by valleys and canyons. It is possible that with the rapid rise of sea level a number of small deep bays developed where presently there are sloughs and valley floors full of sediment. Such narrow deep bays would abound in sea food and provide for a considerable population of sea food eating people. This concept of deep bays existing as a consequence of the rapid rise of sea level was mentioned by Carter (1957). The midden datings obtained so far combined with data on the Holocene transgression substantiate the hypothesis.

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EXCAVATIONS: ISAACS PROPERTY*

The UCLA excavations were limited to 3 test trenches on the property of Dr. John Isaacs. Test Trench 1 was placed in the center of the lot in approximately a north-south direction and extended 35 feet from the top of the knoll (where the sandstone bedrock extends above the surface) to the area where most of the dark midden had been removed. The width of the trench varied from 3 to 5 feet, to preserve the perennial bushes and to allow room for back dirt. The deposit of Test Trench 1 varied in depth, from 6 to 26 inches (Plate 6 F. Figures 2 A, Map 4).

Test Trench 2 was excavated roughly parallel to, but 40 feet east of Test Trench 1. It consisted of 5 pits, 5 by 5 feet, oriented in approximately a north-south direction. Deposits in this area varied from 48 inches at the north end of the trench to 12 inches at the south end. (Fig. 2 B, Map 4)

Test Trench 3 was 20 by 3 feet, at right angles to Test Trench 1 and 19 feet east (Map 4). The depth varied from 12 to 18 inches, but excavations were halted before the sterile subsoil was reached.

Stratigraphy

All three trenches revealed similar deposits and rather simple stratigraphy (Fig. 2), as described by Shumway in the first paper of this series.

There are some interesting variations in the nature of both the dark midden (Stratum A_1) and the compact lime-impregnated Stratum A_2, which suggests a reasonable explanation for the formation of the lime deposit in Stratum A_2. At two places in the excavation the midden appears to be relatively undisturbed: the north end of Trench 1 and the north end of Trench 2. In this area of Trench 2 the dark midden (Stratum A_1) is 2 1/2 to 3 feet deep and the "lime pan" (Stratum B_2) is 1 to 2 feet thick (Fig. 2 B). At the north end of Trench 1 (Pits 0, 1, 2, 3) the dark midden (Stratum A_1) is only 6 inches to 1 foot deep and the "lime pan" (Stratum A_2) is only 6 inches thick in the thickest point. This correlation between the amount of lime deposit and the amount of midden suggests that the lime is formed by leaching of the shells in the upper portion of the midden. This is further supported by two additional factors: 1) If the midden rests on consolidated sand, clay and sandstone, percolation of the lime from a lower level seems highly unlikely. 2) Burials 9, 10, and 11 all located in Trench 1 were found largely in the limy Stratum A_2, however, in all three cases the uppermost portions of the skeletons extended into the dark midden of Stratum A_1. There were no indications that these burials were placed in pits dug into Stratum A_2, but on the contrary the demarcation between Stratum A_2 and Stratum A_1 was continuous and uninterrupted in the immediate vicinity of the burials, suggesting that the lime deposit formed subsequent to the time of the burials. With this information it seems reasonable to assume that the lime of Stratum A_2 formed as a result of leaching of shells in the upper portion of the midden and that it represents a formation which developed contemporaneously with and subsequent to the formation of the upper portion of the midden. Furthermore, the variation of the thickness and compactness of Stratum A_2 suggests that these attributes are due to the amount of shell present in the overlying midden and at present can not be interpreted directly in terms of time differences.

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Artifacts

The raw materials for nearly all the artifacts are found locally. Outcroppings and floats of granites and metamorphics are readily available. The Poway Conglomerate, found throughout the southwestern part of San Diego County contains cobbles of basalt, basalt porphyry and other fine-grained volcanics. The ground stone tools are generally made of granite and sandstone, while the flaked stone tools are restricted to fine grain basalts, quartzite, felsite, quartz and jasper. Felsite and jasper are generally limited to the more finely chipped implements while other fine-grained materials exhibit a wide range of workmanship. A single flake of obsidian found in Stratum A_2 and the presence of a few flakes and artifacts of jasper suggest contact with the interior, while a steatite doughnut-shaped stone suggests contact with Santa Catalina Island.

The dimensions of the artifact types and their vertical distribution in the midden is given in Table 2. Because of the disturbed nature of much of the midden at the Scripps Estates Site I, vertical distribution is given only in terms of lower or upper midden. Lower midden is equated with the lime impregnated Stratum A_2 and the upper midden is equated with the dark loose Stratum A_1. Though this is an imperfect division it illustrates that most artifact types are found throughout the depth of the midden and that no cultural change can be discerned with the small sample we now have.

Flaked Stone Implements: The flaked implements show a wide range of proficiency of stone working technique, including very well made, small, pressure-flaked scrapers, large percussion flaked tools which on first observation appear to defy classification, and several classes of implements intermediate in quality of workmanship. The artifact types described below are defined from the formal aspects of the specimens, with the quality of workmanship considered only secondarily.

The largest class of implements is unifacially flaked tools presumably used for scraping and probably in some cases for chopping.

Scraper planes are plano-convex in cross section with the planar face being formed by a fracture face or the removal of several flakes. At least two variations are present in the type. Variant A (Plate 2, A) is made on large primary flakes with crude percussion flaking along one edge. The convex face is formed by the cortex of the pebble and there is no retouching. Variant B (Plate 2, B-F) is smaller though having a wide size range, and exhibits a more well-controlled percussion technique. The back or convex surface is formed by the removal of a series of flakes at a steep angle along 1/4 to the

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entire periphery with occasional retouching.

Small domed scrapers (Plate 2, G-H) resemble the small scraper planes but are distinguished from them by a much finer workmanship. They are steeply flaked with well-controlled percussion and pressure flaking around 3/4 of the periphery. The remaining 1/4 of the periphery often shows a portion of a striking platform. These scrapers represent the finest stone chipping recovered from the site.

Rectangular side scrapers are made on large oblong or rectangular flakes and are flaked on the long edges. Here again variations occur. Variant A (Plate 2, I) is made on large irregularly formed flakes, crudely percussion-flaked along one edge. Variant B (Plate 2, J-L) is made on uniformly made flakes, roughly rectangular with parallel sides and with a striking platform and bulb of percussion at one end. One or both long edges are unifacially and occasionally bifacially percussion-flaked by a well-controlled method.

Thumbnail scrapers (Plate 3, A) are made on thin flakes by well-controlled pressure flaking. The single complete specimen is worked along 3/4 of the periphery with the unworked portion exhibiting a fragment of the striking platform. It is oval in outline and plano-convex in cross section.

Pointed scrapers (Plate 3, B-C) are made on primary flakes with one end worked to a point by well-controlled pressure flaking. One specimen is unifacially flaked on alternate faces giving the pointed end a beveled cross section.

Flake scrapers include primary flakes, oval in outline and having secondary pressure-flaking, use chipping or polishing on one or more edges. These have been sometimes termed teshoa flakes in literature of southern California archaeology (Plate 3, D-E). In addition, this category includes primary flakes, percussion-flaked on one or more edges (Plate 3, F-G) and pressure-flaked and use chipped secondary flakes (Plate 3, H-L).

Three *miscellaneous scrapers* do not fit any of the types described above. Two are small and steeply flaked by pressure and percussion techniques and are trapezoidal in cross section. The smaller one is ovoid in outline and worked around the entire periphery (Plate 3, N). The larger one is rectangular, pressure-flaked on 3 edges and exhibits 2 well worked corners which may have been used for engraving (Plate 3, M). The third specimen is a large end scraper made on a split pebble and crudely percussion-flaked at one end (Plate 3, O).

Chopping tools, although considerably fewer than the scraping implements, are the second largest class of chipped stone artifacts. Choppers are of two types. *Pebble choppers* (Plate 3, P-Q) are made on waterworn pebbles by bifacial percussion-flaking along 1/2 to 3/4 of the periphery. The worked edge has varying amounts of battering from sharply worked edge to an edge which is rounded and dulled. The second type is the *flake chopper*, made on large flakes and with two variations. Variant A specimens are thick flakes exhibiting secondary percussion-flaking along one or more edges. Variant B specimens are thick irregular flakes modified only by battering on one or more edges (Plate 3, R-S).

A *pick* (Plate 3, T) is made on a thick flake, elongate V-shaped in outline and biconvex in cross section. It is bifacially percussion-flaked along the long edges and has a blunt point and irregular butt.

The one projectile point (Plate 6, A) recovered is small and very finely pressure-flaked. Though fragmentary it appears to have been triangular in outline with a concave base, and is the only artifact made of quartz in this collection. This type of point is very common in the late sites in San Diego County (Meighan, 1954). A few other such points have been picked up on the site by people living in the vicinity. Generally found on or near the surface of the site, these artifacts are, no doubt, intrusive from a later period and should not be considered part of the artifact assemblage under discussion here.

A fragmentary object which may be a portion of a crescent is bifacially percussion-flaked with limited retouching occurring along the edges (Plate 4, A). It is lenticular in cross section and has one rounded end, the other end being broken. One edge is concave while the second is nearly straight, being only slightly convex, It may be the base of a crude or partially finished leaf-shaped point, but the slight curvature of the specimen suggests that it is a fragment of a crescent. Unfortunately it was found in a disturbed refuse pit containing nails and bricks, and its association with the remainder of the assemblage is uncertain.

Cores are classed in 3 types: irregular multiface (Plate 4, B) with flakes removed from all faces; Platform cores (Plate 4, C-D) with a platform from which flakes are removed around the periphery at nearly 90° angle. And Polar cores (Plate 4, E) with large flakes removed by bifacial flaking on a relatively narrow end.

Ground edge cores (Plate 4, F) exhibit small areas of "grinding" on the edges between the flake scars. These areas are relatively smooth, but appear to have been the result of gentle pounding or crushing rather than actual grinding.

Hammerstones are pebbles which have been battered by use in hammering. A certain amount of variation exists which allows 3 types to be described. Core hammers (Plate 4, G-I) are simply multiface and platform core which have been subsequently used for pounding. Pebble hammerstones (Plate 4, J-K) are usually flat ovoid "beach pebbles" battered on the edges. Pestle-like hammerstones (Plate 4, L-M) are elongate pebbles with an end battered. Their general shape and use pattern resembles crude pestles, suggesting that they were used as such.

Ground Stone Objects: Objects in this category are largely ground through use rather than by purposeful shaping; however, purposeful shaping by grinding does occur.

Manos (Plate 4, N-P) are made on cobbles and are unshaped except through use. Outlines vary from round to elongate oval and both biface and uniface occur. Occasionally the outline will be somewhat altered by pecking at one or both ends.

Basin metates are roughly oval in outline with a few tending toward a rectangular shape. The basin is generally more than 1/2 as deep as the specimen is thick. Three variations are present. Variant A (Plate 5, A) is a slab, unshaped except by use. Variant B (Plate 5, B) has a shaped exterior with a rounded lip. Variant C (Plate 5, C) has a shaped exterior with an abrupt break in the line at the edge of the upper surface giving it a sharper lip than that of Variant B.

In addition to these metates there are ten fragments of sandstone which exhibit ground areas. Some of these are probably small fragments of metates, however, several have concave surface which have a narrow curvature and may represent a type of whetstone.

A single perforated sandstone fragment was recovered (Plate 6,B). It is irregular in outline, roughly rectangular in cross section and has a single conical hole drilled through the center. It may represent a fragment of a large ornament.

A single "doughnut-shaped stone" was recovered from the excavation and a second was recovered from the surface of the site by Dr. George Shumway (Plate 6, D-E). Both specimens are fragmentary with about 1/2 of the stone being present. The holes are biconical with rough surfaces resulting from the drilling process. The smaller specimens recovered from the surface have a finely ground exterior. The second specimen exhibits the results of pecking although the surface is somewhat smoothed. Due to the small size of these doughnut stones the usual interpretation as digging stick weights does not appear to be valid in this instance. Interpretation as ornaments, possibly large beads, seems more reasonable.

Bone tools: Three fragmentary pieces of worked bone were recovered. A flat rectangular splinter has a partially ground edge and probably represents a piece of bone detritus removed from a larger piece by grooving and breaking. The second piece is a flat ground object, in fragmentary condition, with two ground faces and a rounded edge. The third piece is a tip fragment of a pointed object, possibly a projectile point or fish gorge (Plate 6, C).

TABLE 2: Dimensions and Vertical Distribution of Artifact Types.

Artifact types	Dimensions (in mm.)						no. of specimens	location in midden		
	Length		Width		Thickness			upper	lower	disturbed or surface
	Min.	Max.	Min.	Max.	Min.	Max.				
Scrapers										
Scraper Planes										
Variant A	96	110	71	100	30	74	4	3	--	1
Variant B	40	74	33	63	19	48	20	9	5	6
Small Domed Scrapers	34	39	30	36	14	20	3	2	1	--
Rectangular Side S Scrapers										
Variant A	82	125	41	68	18	30	5	4	--	1
Variant B	62	93	61	76	21	32	5	5	--	--
Thumbnail scraper (one specimen complete)	26		22		8		3	2	1	--
Pointed scrapers	59	69	42	54	14	17	2	2	--	--
Flake Scrapers	20	82	15	66	4	30	24	10	9	5
Misc. Scrapers	22	91	16	48	21	43	3	1	1	1
Choppers										
Cobble Choppers	64	101	42	74	24	62	10	6	3	1
Flake Choppers										
Variant A	46	64	39	61	19	31	3	2	1	--
Variant B	60	74	41	56	17	38	7	4	1	2
Projectile point	27		--		3		1	1	--	--
Crescent?	--		23		12		1	--	--	1
Pick	70		31		27		1	--	--	1
Cores										
Multiface	66	85	47	71	36	48	4	4	--	--
Platform (one specimen complete)	58		47		47		2	2	--	--
Polar	83		72		54		1	1	--	--
Edge ground core	71	84	55	58	47	54	2	1	1	--

TABLE 2 (continued)

Artifact types	Length Min.	Length Max.	Width Min.	Width Max.	Thickness Min.	Thickness Max.	no. of specimens	location in midden upper	location in midden lower	location in midden disturbed or surface
Hammerstones										
Core hammers	64	88	50	73	39	59	8	6	1	1
Pebble hammer-stone	62	84	53	72	21	46	2	2	--	--
Pestle-like	inc.		41	63	37	47	2	2	--	--
Manos										
Unshaped uniface	114	117	83	96	55	59	5	2	1	2
Biface	101	127	69	105	41	51	13	8	2	3
Fragments	Too fragmentary to measure						3	3	--	--
Metates										
Variant A	inc.		270		74		3	1	--	2
Variant B	Too fragmentary for measurements						5	1	--	4
Variant C	459		356		115		3	1	1	1
Misc. fragments							10	7	1	2
Drilled sandstone Fragment	63		42		18		1	1	--	--
Doughnut shaped Stones	35 to 48 (Dia.)				23 to 35 (height)		2	--	1	1
Bone tools										
Detritus	26		14		4		1	1	--	--
Ground Frag.	25		5		3		1	1	--	--
Pointed obj.	24		4 diameter				1	1	--	--

Burials

Three of the 16 burials were excavated and two more partially exposed by the UCLA crew. The burial numbers from the UCLA excavations were integrated with the burials recovered by Moriarty and Shumway. Only the burials excavated by the UCLA crew are described here. Burials 9 and 10 are now housed at the Department of Anthropology-Sociology, University of California, Los Angeles. All other burials are in the hands of Mr. James Moriarty and Dr. George Shumway and are being further studied.

Burial 1 (Plate 7, B-C) was found in pits 7 and 8 of Trench 2. It was very fragmentary consisting of one femur, tibia and fibula, a few ribs and a fragmentary skull. It was thoroughly surrounded by the lime deposit of Stratum A_2 and rested on the underlying sand of Stratum A_3. Although in fragmentary condition the burial position could be discerned. It lay in a flexed position, probably on its right side with the head oriented toward the north. A variant C basin metate was inverted over the skull, but no other artifacts were found in association.

Burial 9 (Plate 7, A) was in the west wall of Pit 6, Trench 1. It was tightly flexed on the left side with the head oriented toward the northwest. The left arm was placed under the head and the right arm between the knees. The lower portion of this burial was located in Stratum A_2 but the skull protruded into the overlying Stratum A_1. The skull was only 3 1/2 inches below the present surface; however, it appears that much of the upper Stratum A_1 has been removed from this area. The long bones were very fragmentary and no measurements could be obtained except from the skull.

Burial 10 (Plate 6, G) was in Trench 1, Pit 4. It was loosely flexed, on the right side with the head oriented east, southeast. Both arms were placed between the knees. Like Burial 9, Burial 10 was partially enclosed in Stratum A_2, but the upper portion extended into Stratum A_1. This burial was in a fair condition and a set of measurements was taken from it. It appears to be an adult female. No artifacts were found in association. At the highest point Burial 10 was 10 inches from the surface but here again the surface appears to have been lowered by prior removal of the upper midden.

Burial 11 was in the east wall of Trench 1 between Pits 4 and 5 and only 2 feet from Burial 10. It was represented by a fragmented skull and the ends of a tibia and femur protruding from the wall at 13 to 15 inches below the surface. The burial position could not be ascertained, but it appears that the head was oriented in a southerly direction.

Burial 12 was in the northwest corner of Pit 1, Trench 3 and was represented by only a skull fragment. Work was halted before it could be determined whether more remains of the burial were present.

Summary

The Scripps Estates Site I presents an interesting list of traits including large numbers of scraping, chopping and pounding tools which have a wide range of workmanship. These include crudely percussion-flaked scrapers and choppers, small finely flaked domed and thumbnail scrapers, basin metates, and unshaped manos, small spheroid, doughnut-shaped stones with drilled biconical holes, and pointed bone objects. In addition to these traits, the spire-lopped olivella shell beads and Pismo clam disc beads reported by Moriarty and Shumway may be included along with stone discoidals collected from the site by Dr. Carl Hubbs (personal communication). Burials are flexed and placed on their side, with irregular orientation tending toward the north. Burials are found in groups rather than individually. Burial goods occur rarely and metates are sometimes inverted over the individual.

The ecological remains in the midden would indicate that shellfish were an important food source with fish being secondary. The relatively large number of grinding implements suggest that seed gathering was also important and the very few mammal bones show that hunting of large mammals was not often undertaken.

Discussion and Conclusions

In order to place the Scripps Estates site in any cultural chronology it appears necessary to first review the major works done in San Diego County that deal with "La Jollan type" material and present the divergent views that exist.

As early as 1929 Malcolm Rogers recognized two distinct older cultures throughout the coastal belt of San Diego County. One, we are told, is characterized by numerous shell middens, found not only on the coast, but as far as four miles inland. "The surface finds from these middens include metates, manos, hammerstones, teshoa-flakes, and a great amount of split stone, but no chipped stone artifacts which may be recognized as finished implements unless it be the teshoa-flakes. Potsherds are entirely absent . . . . Many of the middens produce nothing that would associate them with man, except the split stone." (Rogers, 1929: 457). In this early paper Rogers does not give this "culture" a name, referring to it only as "shell midden" or "Shell-Midden peoples." However, from this description it is clear that this assemblage was what he later (1945) termed the La Jolla culture.

The second "culture" recognized by Rogers in his 1929 paper was the "Scraper maker culture" which he also renamed at a later date (1939) calling it San Dieguito. In 1929 Rogers stated;

> "The Scraper-Maker Culture can be connected through its chipped stone industry, with . . . that of the Shell-Midden peoples; in fact, there is some evidence that the former is an outgrowth of the latter. The numerous flake cores of the middens might easily be prototypes to the scraper planes; at least, they are an essential stage in the construction of the latter." (1929: 466)

It is quite clear that in 1929 Rogers felt that the La Jolla complex preceded the San Dieguito and was the base from which the San Dieguito developed.

In a later paper, however, Rogers reverses the sequence when he states:

> "Immediately after the disappearance of the San Dieguito peoples with their excellent stone-flaking technique, a new stock with a sea food-seed-gathering complex and no ability to work stone moved in . . . . From this time on down until historic time the archaeologic history is well recorded in a succession of numerous shell middens." (1945: 171)

According to Rogers, stratigraphic studies have established that the middens are of three different ages, only the last being definitely Yuman. The earlier cultural manifestation is given the name La Jolla "and its two developmental phases are spoken of as La Jolla I and II." (1945: 171)

La Jolla I, he states, is characterized by basin metates, unshaped manos, a few primary flakes of stone, and an even lesser number of crude, beach cobble choppers. Stone projectile points are absent and unsegregated interment without mortuary offerings was the method of disposing of the dead.

The La Jolla II pattern evolved gradually and is characterized by the common occurrence of stone flaking, increase in the use of metates, burials are more segregated and cemeteries occur. At this time there was apparently contact with the Channel Islands "with the results that typical Channel Island beads and stone digging-weights were included with the burials," which were also often marked with inverted metates. (Rogers 1945: 172)

Harding (1951), in discussing work done by the Museum of Man in the San Diego vicinity, briefly described a site which apparently represents both La Jolla I and II. Very simple flake tools occur in the lower levels and there is a gradual addition of metates and chipped stone tools including a few projectile points. Spire-lopped olivella beads, a shell ring and a "softstone pendant" also occur (1951: 33-35). The midden deposit included shells of clams and scallops from the mud of the sloughs, with occasional mussels from the more open water. Other faunal remains included a few deer bones, fish vertebrae and possibly seal bones.

Neither the site name or number is given by Harding in her short article, but it is presumably the Sorrento site designated SDM-W316 by the San Diego Museum of Man numbering system and SDi-531 in the University of California Archaeological Survey records. This site is dated at 6950±350 years B. P. (Crane and Griffin, 1958), placing it in the same age range as Scripps Estates Site 1. Outline drawings of the five projectile points recovered from this site were made by B. E. McCown and sent to Dr. C. W. Meighan at UCLA. These drawings are reproduced here as Figure 5. They range in length from about 2 cm. to 5 cm. and average about 0.6 cm. in thickness. Little in the way of conclusions can be made on the basis of these outline drawings, but similarities between these points and Pinto points are suggested. Though few in number, the presence of these points in site of this age is certainly significant.

Carter (1957) recognizes the La Jolla Complex in a number of sites in the San Diego area. However, it is most clearly outlined on the Torrey Pines Mesa, where four or five sites (including the Scripps Estates Site I) have yielded choppers, scraper planes, crude flake scrapers and manos and metates. This complex is also suggested for the San Diego River Valley and adjacent coastal area, and in the vicinity of Escondido. However, extremely small artifact inventories from most of these sites make it hazardous to identify them as of the La Jolla culture.

D. L. True (1958) has also reported an early complex from the Pauma Valley area that resembles La Jolla. The complex contains manos, metates, hammerstones, a few discoidals, projectile points and, rarely, steatite doughnut stones. However, the Pauma complex apparently varies in having more numerous projectile points, blades, and also in the presence of crescent stones. In addition to resembling the La Jolla complex, True says of this complex: "Similarities between the Pauma complex and elements of San Dieguito are obvious . . . . However, no conclusions or even close comparisons can be made until there are more data available from the San Dieguito areas and until the status of San Dieguito has been determined" (1958: 262).

The dating of the La Jolla Complex has varied from one extreme to the other. Carter (1957: 369-73) would have the La Jollan industry extend back into the upper part of the last interglacial and preserve a cultural continuum of remarkable stability until the introduction of the Yuman Complex. Carter apparently recognized a division of the La Jolla Complex with the second phase of development marked by finer stoneworking techniques. If I read him correctly, this innovation is attributed to contact with the San Dieguito Complex (presumably originating in the interior) at about 10,000 years ago.

The other extreme in the dating has been advanced by Rogers, who would set the initial date for the La Jolla I Complex at about the beginning of the Christian era (1945).

On one hand, Johnson and Miller (1958) and Krieger (1958) have shown certain shortcomings that cast serious doubt on Carter's work, leaving him little in the way of evidence for third interglacial man. On the other hand, the C-14 date reported from the Scripps Estates I site indicates clearly that Rogers' dating of the La Jolla Complex is too late.

Giving a time range to the La Jolla Complex is still impossible to do with any certainty. We know that the La Jolla Complex was in existence between about 7000 and 5000 years ago. If Rogers' division of La Jolla I and II is correct, then the burial pattern, well-controlled stoneworking technique, shell beads and the doughnut-shaped stone would indicate that the Scripps Estates Site I belongs to the La Jolla II phase. If this is so, it may be assumed that La Jolla I phase predates the Scripps Estates site. However, the possibility that the La Jolla I and La Jolla II division is a reflection of seasonal economic activities rather than differences in time, or that it is the result of poor sampling cannot yet be ruled out.

Our present state of knowledge about the La Jolla Complex is limited and can be but summarized as follows:

The La Jolla Complex is generally defined as being based on a sea food and seed-gathering economy, with a wide range of proficiency in stoneworking technique. The artifact assemblage consists largely of metates and manos, crudely flaked scrapers and choppers, with a limited number of finely made scrapers and a few projectile points, crude hammerstones, and the rare occurrence of other tools and ornaments of steatite, shell and bone. Burials are flexed, placed on their side with a tendency toward a northerly orientation and occasionally accompanied by mortuary offerings. They occur individually and in groups, and occasionally inverted metates or small piles of broken rock are placed over them.

On the basis of variation in burial pattern, the presence and absence of steatite and shell artifacts and the quality of workmanship in stoneworking it has been suggested that the La Jollan Complex be divided into two developmental phases. However, these phases may represent seasonal economic differences or differences in artifact sample rather than differences in time. On the basis of known C-14 dates, it appears that the La Jolla Complex was in existence for some time prior to 7000 years ago and for 2000 or more years after that date.

The geographical boundaries of the La Jolla Complex are still undefined. It is known to extend along the San Diego coast, probably into Baja California and possibly as far north as Orange County. The eastern extension is likewise uncertain, but both Carter's site in the Escondido area and True's Pauma Complex suggest that the La Jolla Complex or variation on the same general pattern extends considerably farther inland than the 4 mile limit reported by Rogers in 1929.

Relationships between the La Jolla Complex and those of the interior desert region remain to be illustrated by field work. The occurrence of obsidian and jasper in the Scripps Estates Site I suggest contact from that direction.

Steatite recovered from La Jollan sites suggest contact with Sante Catalina Island. The Little Harbor Site (Meighan, 1959) which has been dated by carbon-14 at 3880 + 250 shows little resemblance to the La Jolla Complex with only the doughnut-shaped stones, scraper planes and possible manos and metates being shared.

Detailed relationships with other coastal complexes cannot now be defined because of lack of data. Wallace (1955), however, has placed the La Jolla Complex in Horizon II of his four broad temporal divisions for the Southern California Coast. The data obtained from the Scripps Estates Site I support the placement of the La Jolla Complex in the same horizon as the Topanga sites (LAn-1 and LAn-2), Little Sycamore, Zuma Creek, Malaga Cove and the Oak Grove culture. With the exception of Malaga Cove and the Oak Grove culture all share a rather large series of crude core and flake tools as well as manos and metates in numbers. The La Jolla Complex on the other hand lacks the number of points and blades and the few mortars and pestles reported from the northern sites. Wallace estimates the milling stone assemblages to be 2000 to 5000 years old. The C-14 dates now available from San Diego sites would extend the initial date back to about 7000 years in that area, and it seems reasonable to assume that an initial date of 5000 years is too conservative for this horizon throughout the southern coast.

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University of California
Los Angeles

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EXPLANATIONS OF MAPS, FIGURES AND PLATES

MAP 1: Location of Coastal Sites of North San Diego County
MAP 2: Contour map of vicinity of Scripps Estates Sites
MAP 3: Location of Burials at Scripps Estates Site I
MAP 4: Scripps Estates Site I, Burial Locations and Plan of Excavations, 1958-59

FIGURE 1: Profile of Shumway-Moriarty Excavation at Scripps Estates Site I
FIGURE 2: Profiles of Test Trenches 1 and 2, UCLA Excavations
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FIGURE 4: Post-Glacial Sea Level Changes
FIGURE 5: Outline Drawings of Projectile Points from Sorrento Valley Site after B. E. McCowen. (Points are actual size)

PLATE 1: Manos, Shell Beads and Flaked Tools from Scripps Estates Site I
  A. Manos
  B. Shell beads
  C. Flaked tools

PLATE 2: Scrapers from Scripps Estates Site I. B is 80 mm long, all others are to scale.
  A. Variant A scraper plane
  B-F. Variant B scraper planes
  G-H. Small domes scrapers
  I. Variant A side scraper
  J-L. Variant B side scrapers showing outline and view of striking platform

PLATE 3: Scrapers, Choppers and Pick from Scripps Estates Site I. A is 25 mm long, all others are to scale.
  A. Thumbnail scraper
  B-C. Pointed scrapers
  D-I. Flake scrapers
  J-L. Miscellaneous scrapers
  M-N. Cobble choppers
  O-P. Variant B flake choppers
  Q. Pick

PLATE 4: Crescent?, Cores, Hammerstones and Manos from Scripps Estates Site I. G is 83 mm long, all others are to scale.
  A. Crescent?
  B. Multiface core
  C-D. Platform cores
  E. Polar core
  F. Ground edge core (arrow designates ground edge)
  G-I. Core hammers
  J-K. Pebble hammerstones
  L-M. Pestle-like hammerstones
  N-O. Biface manos
  P. Uniface mano

PLATE 5: Metates from Scripps Estates Site I. C is 459 mm long, all others are to scale.

- A. Variant A deep basin metate
- B. Variant B deep basin metate
- C. Variant C deep basin metate

PLATE 6: Miscellaneous Artifacts, Test Trench 1 and Burial 10 from Scripps Estates Site I. All artifacts are to scale.

- A. Projectile point
- B. Perforated sandstone object
- C. Pointed bone object
- D-E. Doughnut-shaped stones
- F. View of Test Trench 1 with Burial 11 and 10 *in situ*
- G. View of Burial 10 *in situ*

PLATE 7: Burials 9 and 1 at Scripps Estates Site I

- A. Burial 9 and steatite doughnut-shaped stone (arrow) *in situ*
- B. Burial 1 viewed from above
- C. Burial 1 showing stratigraphic position (arrow indicates break between strata A^1 and A^2).

PLATE 8: Burials 3, 13 and 15 at Scripps Estates Site I

- A. Burial 3 *in situ*
- B. Burial 13 *in situ*
- C. Burial 15 *in situ* with Metate placed over it. Only a portion of the burial is visible between Metate and white sign.

REFERENCES

Carter, G. F.
1957 Pleistocene Man at San Diego; Johns Hopkins Press, Baltimore

Crane, H. R., J. B. Griffen
1958 University of Michigan Radiocarbon Dates III; Science, Vol. 128, No. 3332, pp. 117-123, Lancaster

Cornwall, I. W.
1956 Bones for the Archaeologist, Macmillan Company, New York

Curray, Joseph Ross
1959 Sediments and History of the Holocene Transgression Continental Shelf, Northwest Gulf of Mexico, A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Oceanography, University of California, Los Angeles, Scripps Institution of Oceanography.

Emery, K. O.
1945 Mineralogy of Caliche from San Diego County, California, Bulletin of the Southern California Academy of Science, Vol. 44, Pt. 3, pp. 130-135

1950 Ironstone Concretions and Beach Ridges of San Diego County, California, California Journal of Mines and Geology, Vol. 46, pp. 213-221

Hanna, M. A.
1926 Geology of the La Jolla Quadrangle, California, University of California Publication Bulletin, Department of Geological Sciences, Vol. 16, No. 7, pp. 187-246

Harding, Mabel
1951 La Jollan Culture, El Museo, Vol. 1, No. 1, Museum of Man, San Diego

Hertlein, L. G. and U. S. Grant, IV
1939 The Geology and Paleontology of the Marine Pliocene of San Diego, California. Pt 1 Geology, San Diego Society of Natural History, Memoir, Vol. 2, pp. 1-72

1954 Geology of the Oceanside-San Diego coastal area, Southern California, California Division of Mines Bulletin 170, Chapter II, pp. 53-63

Johnson, Frederick and John P. Miller
1958 Review of Pleistocene Man at San Diego, American Antiquity, Vol. 24, No. 2, pp. 206-210, Salt Lake City

Kroeber, A. L.
1953 Handbook of the Indians of California, California Book Company Ltd., Berkeley, California

Krieger, Alex D.
1958 Review of Pleistocene Man at San Diego, *American Anthropologist*, Vol. 60, No. 5, pp. 974-978, Menasha

Meighan, Clement W.
1954 A Late Complex in Southern California Prehistory, *Southwestern Journal of Anthropology*, Vol. 10, No. 2, pp. 255-264, Albuquerque.

1959a California Cultures and the Concept of an Archaic Stage, *American Antiquity*, Vol. 24, No. 3, pp. 289-305, Salt Lake City

1959b The Little Harbor Site, Catalina Island: An Example of Ecological Interpretation in Archaeology, *American Antiquity*, Vol. 24, No. 4, pp. 383-405, Salt Lake City

Meighan, Clement W., D. M. Pendergast, B. K. Swartz, Jr., and M. D. Wissler
1958 Ecological Interpretation in Archaeology: Part I, *American Antiquity*, Vol. 24, No. 1, pp. 1-23, Salt Lake City

Merriam, C. H.
1955 *Studies of California Indians*, University of California Press, Los Angeles, California

Rogers, Malcolm J.
1929 The Stone Art of the San Dieguito Plateau, *American Anthropologist*, Vol. 31, pp. 454-467, Menasha

1939 Early Lithic Industries of the Lower Basin of the Colorado River and Adjacent Desert Areas, *San Diego Museum Papers No. 3*, San Diego, California

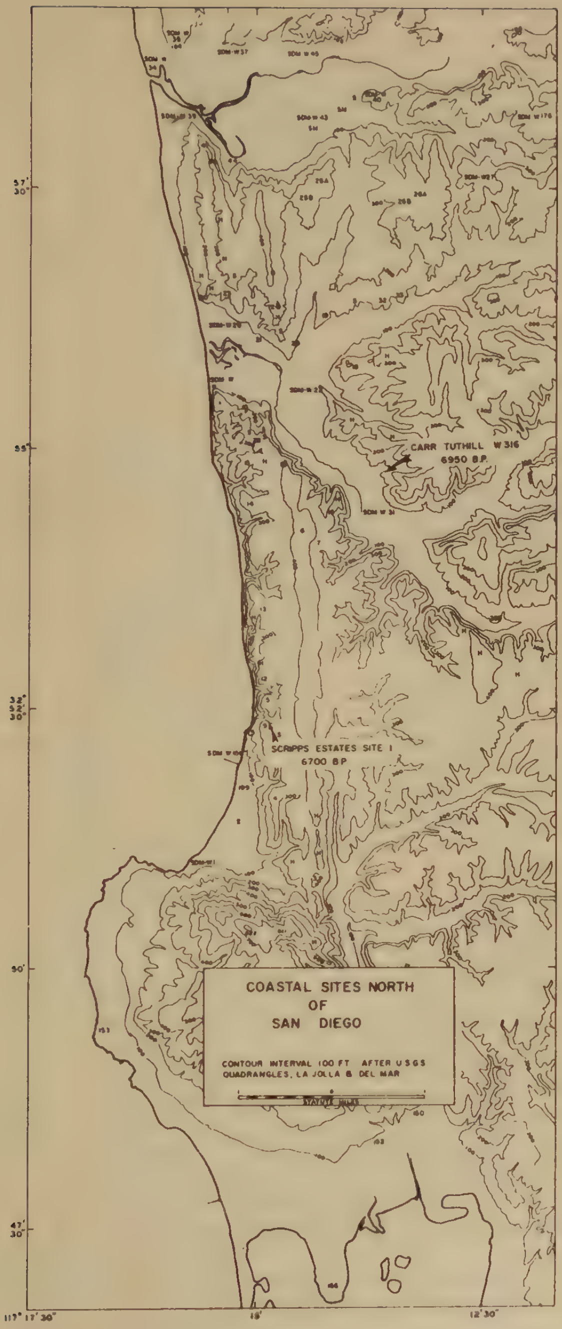
1945 An Outline of Yuman Prehistory, *Southwestern Journal of Anthropology*, Vol. 1, No. 2, pp. 157-198, Albuquerque

1958 San Dieguito Implements from the Terraces of the Rinon-Pantano and Rillito Drainage System, *The Kiva*, Vol. 24, No. 1, Arizona State Museum, University of Arizona, Tucson

True, D. L.
1958 An Early Complex in San Diego County, California. *American Antiquity*, Vol. 23, No. 3, pp. 255-63. Salt Lake City

Tuthill, Carr and A. A. Allanson
1955 Ocean bottom Artifacts. *The Masterkey*, Vol. 28, No. 6, pp. 222-232, Southwest Museum, Los Angeles

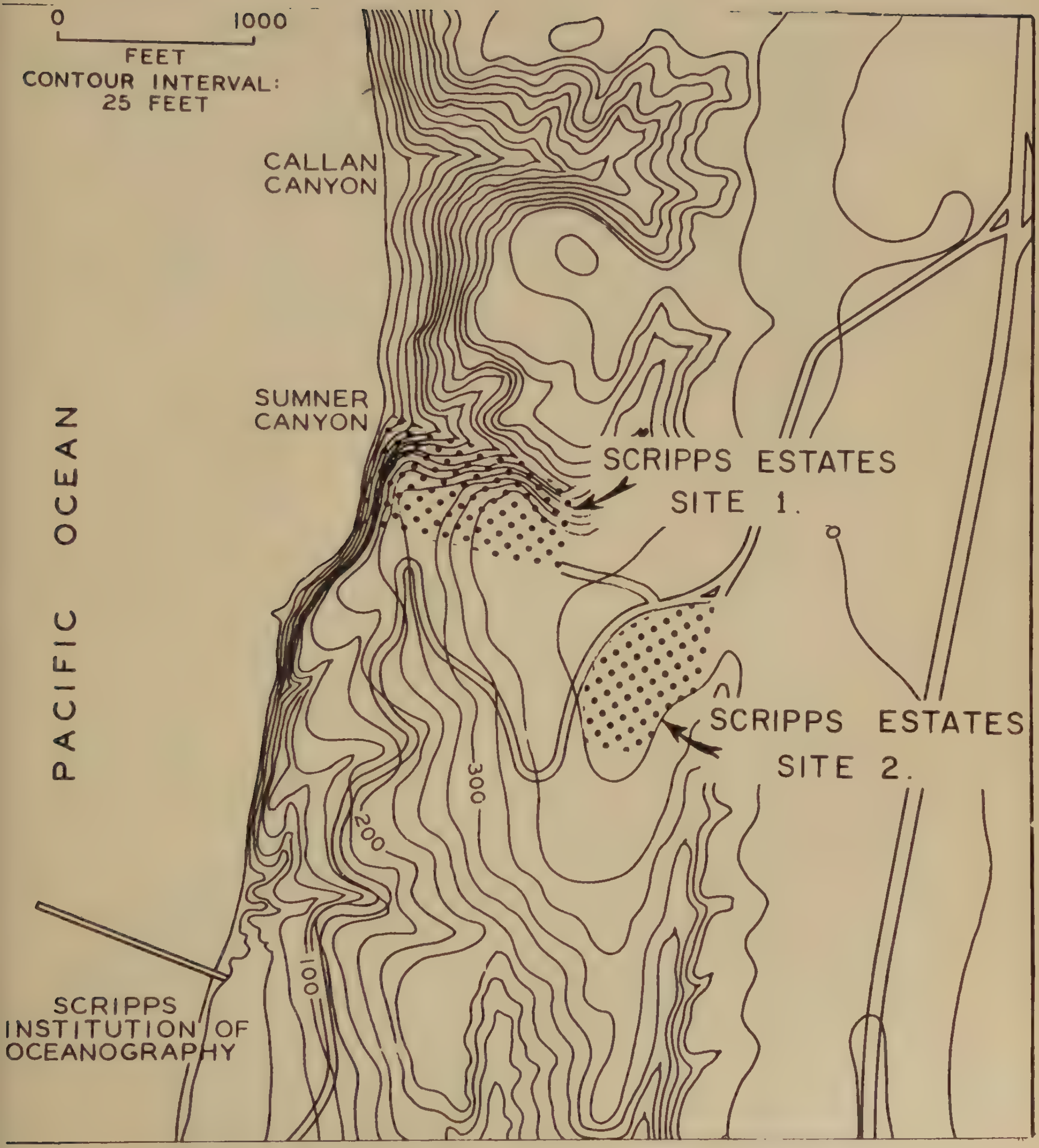
Wallace, William J.
1955 A Suggested Chronology for Southern California Coastal Archaeology. *Southwestern Journal of Anthropology*, Vol. 11, No. 3, pp. 214-230, Albuquerque.



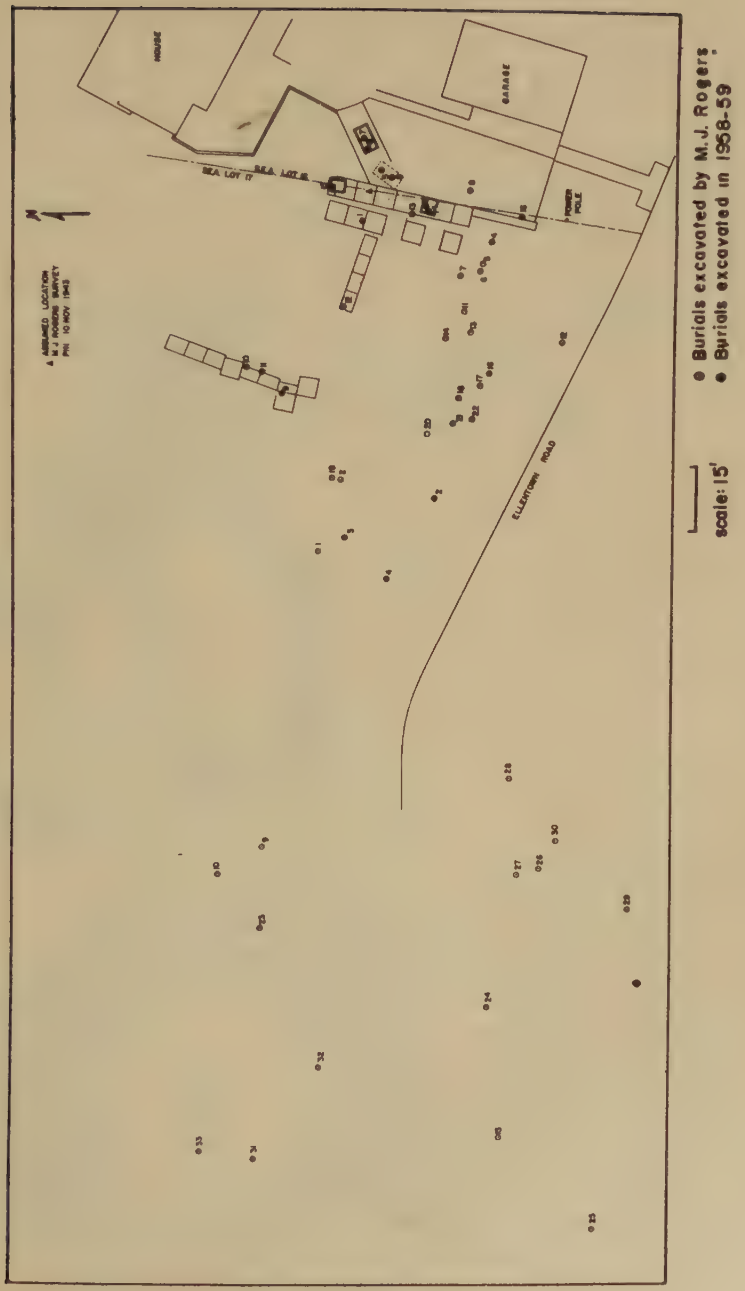
SDM W 37
SDM W 39
SDM W 43
SDM W 176
CARR TUTHILL W 316
6950 B.P.
SDM W 31
SCRIPPS ESTATES SITE 1
6700 B.P.
COASTAL SITES NORTH
OF
SAN DIEGO
CONTOUR INTERVAL 100 FT AFTER USGS
QUADRANGLES, LA JOLLA & DEL MAR
STATUTE MILES
57'
30"
55'
32°
52'
30"
50'
47'
30"
117° 17' 30"
15'
12' 30"

MAP I: Coastal Sites of North San Diego County

(858)

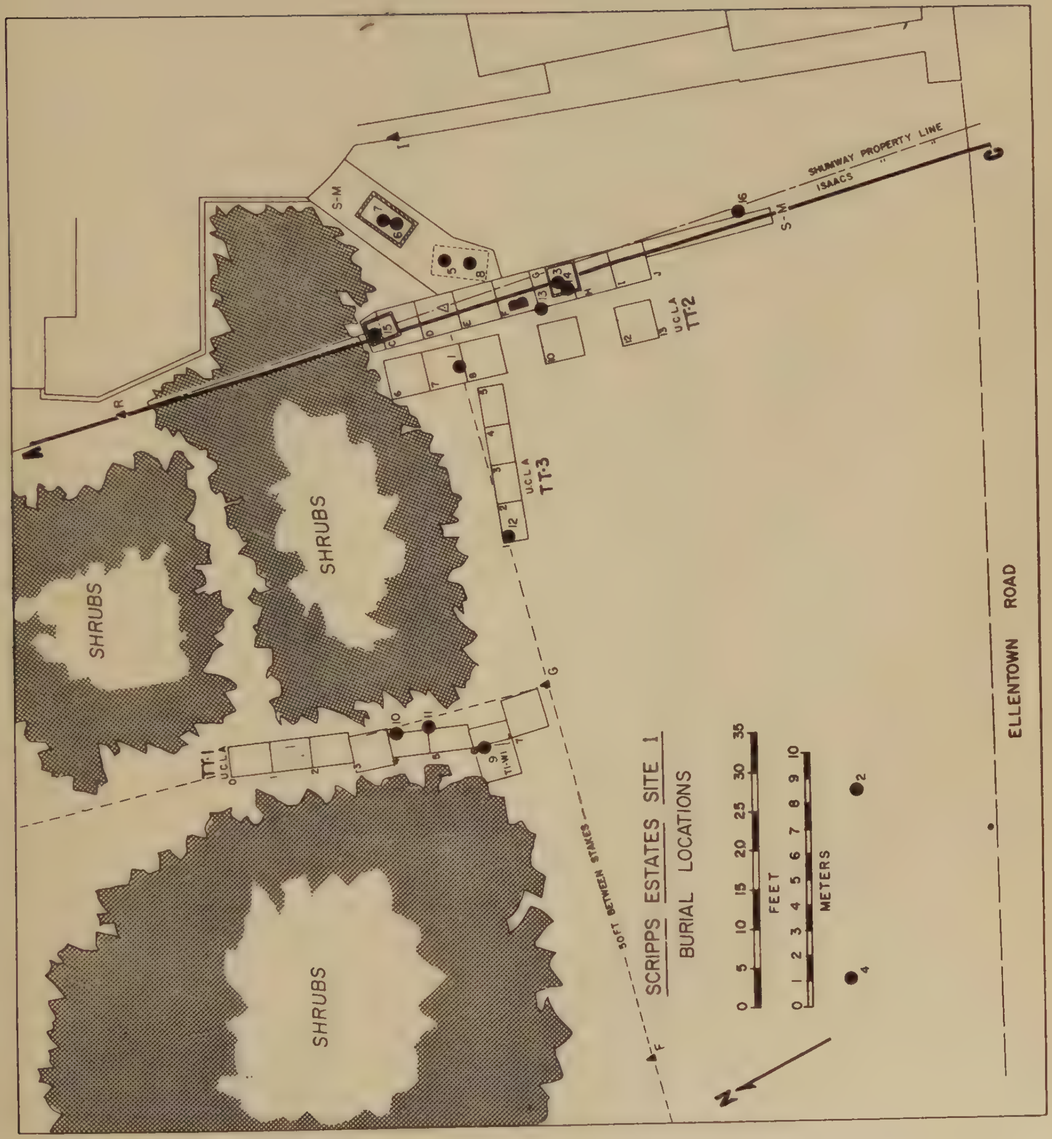

0
1000
FEET
CONTOUR INTERVAL: 25 FEET
CALLAN CANYON
SUMNER CANYON
PACIFIC OCEAN
SCRIPPS ESTATES SITE 1.
SCRIPPS ESTATES SITE 2.
300
200
100
SCRIPPS INSTITUTION OF OCEANOGRAPHY

MAP 2: Contour Map of Vicinity of Scripps Estates Sites


HOUSE
GARAGE
S.E.A. LOT 17
S.E.A. LOT 18
POWER POLE
ELLENTOWN ROAD
N
ASSUMED LOCATION
M J ROGERS SURVEY
PIN 10 NOV 1943
● Burials excavated by M.J. Rogers
● Burials excavated in 1958-59
scale: 15'

MAP 3: Location of Burials at Scripps Estates Site I

(862)


SCRIPPS ESTATES SITE 1
BURIAL LOCATIONS
SHRUBS
SHRUBS
SHRUBS
ELLENTOWN ROAD
SHUMWAY PROPERTY LINE
ISAACS
S-M
S-M
U.C.L.A TT-1
U.C.L.A TT-2
U.C.L.A TT-3
T1-W1
50 FT BETWEEN STAKES
FEET
METERS
0 5 10 15 20 25 30 35
0 1 2 3 4 5 6 7 8 9 10
A
C
E
F
G
I
R
N

MAP 4: Scripps Estates Site I, Burial Locations and Plan of Excavations, 1958-59

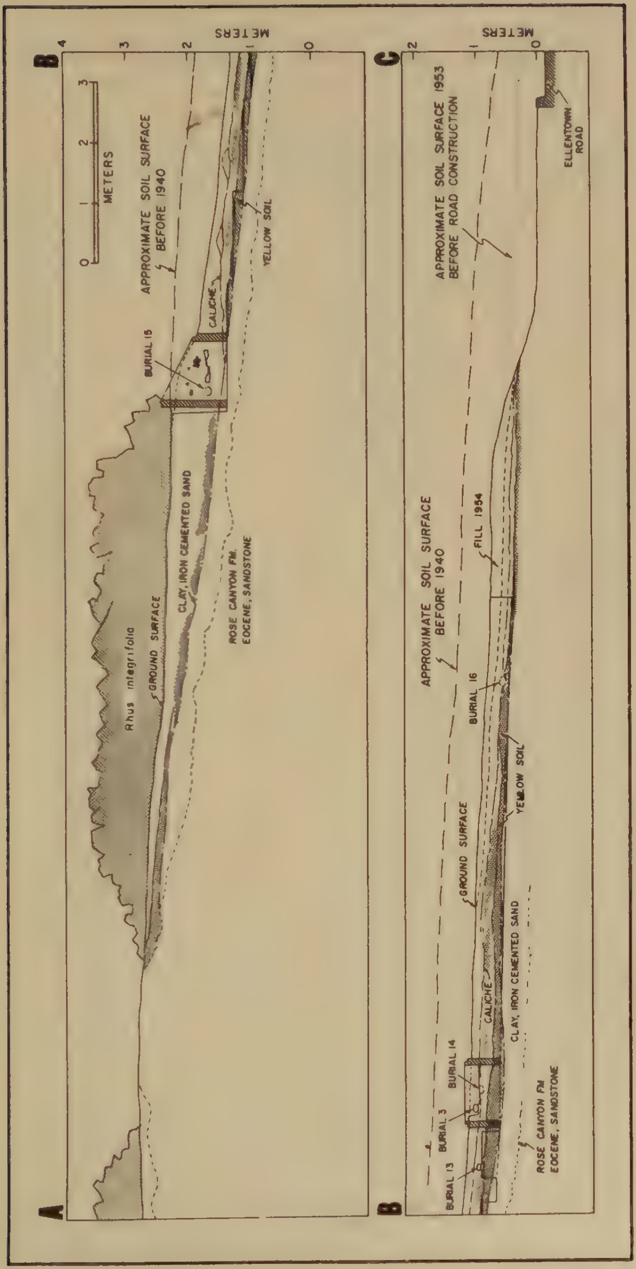

A
B
METERS
4
3
2
1
0
0 1 2 3
METERS
APPROXIMATE SOIL SURFACE BEFORE 1940
CALICHE
YELLOW SOIL
BURIAL 15
Rhus integrifolia
GROUND SURFACE
CLAY, IRON CEMENTED SAND
ROSE CANYON FM. EOCENE, SANDSTONE
C
B
METERS
2
1
0
ELLENTOWN ROAD
APPROXIMATE SOIL SURFACE 1953 BEFORE ROAD CONSTRUCTION
FILL 1954
APPROXIMATE SOIL SURFACE BEFORE 1940
BURIAL 16
YELLOW SOIL
GROUND SURFACE
CLAY, IRON CEMENTED SAND
CALICHE
BURIAL 14
BURIAL 3
BURIAL 13
ROSE CANYON FM EOCENE, SANDSTONE

FIGURE 1: Profile of Shumway-Moriarty Excavation at Scripps Estates Site 1

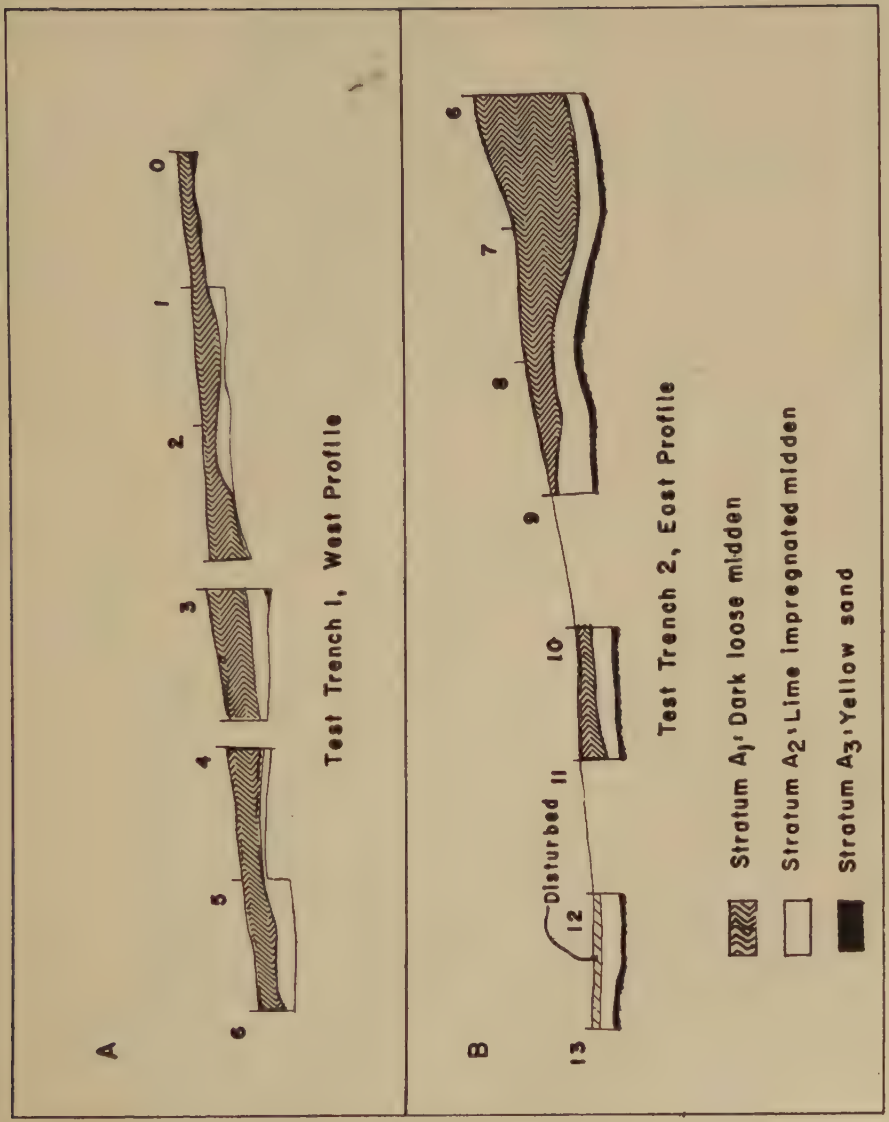

A
0
1
2
3
4
5
6
Test Trench 1, West Profile
B
6
7
8
9
10
11
12
13
Disturbed
Test Trench 2, East Profile
Stratum A_1: Dark loose midden
Stratum A_2: Lime impregnated midden
Stratum A_3: Yellow sand

FIGURE 2: Profiles of Test Trenches 1 and 2, UCLA Excavations

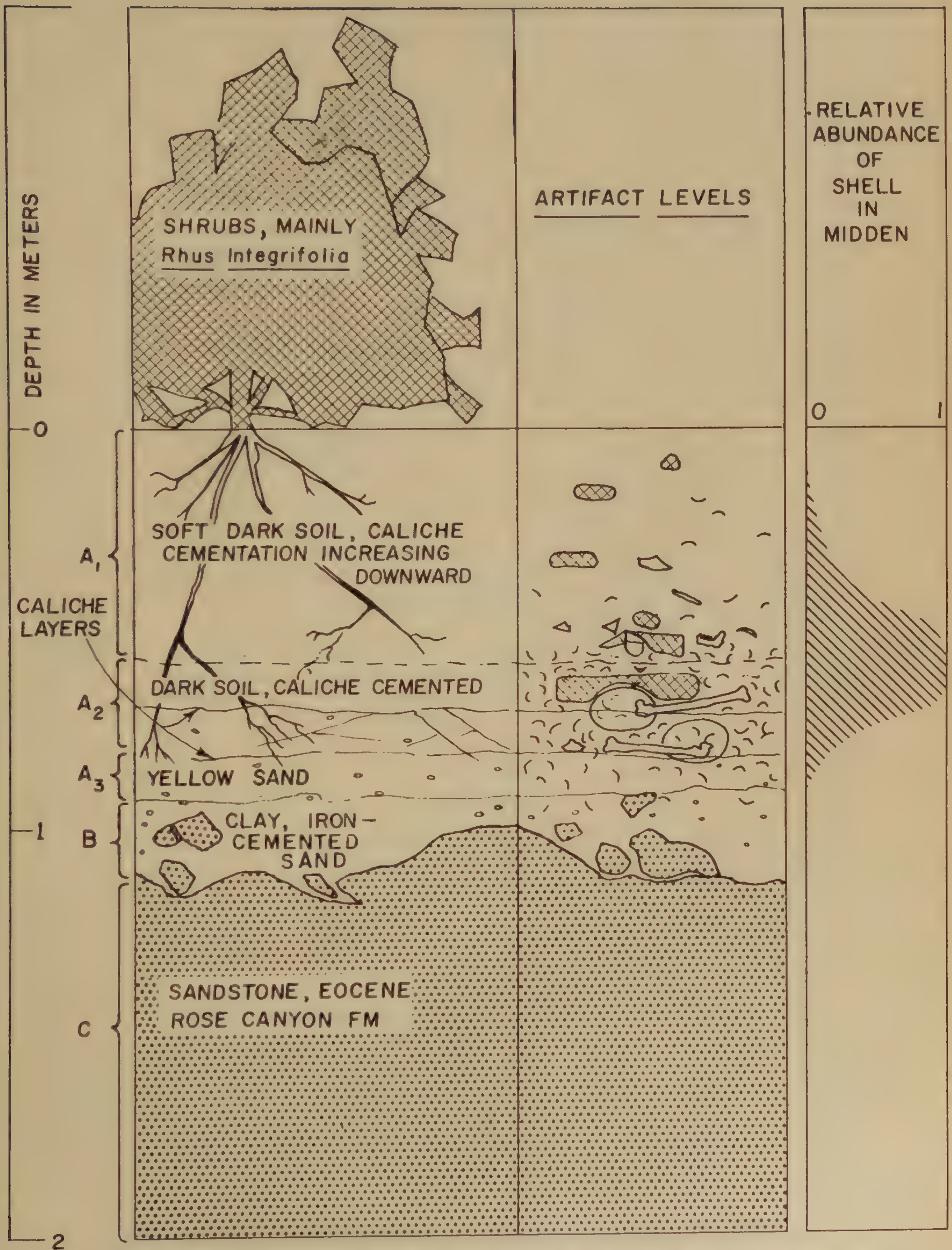

DEPTH IN METERS
0
1
2
SHRUBS, MAINLY
Rhus Integrifolia
ARTIFACT LEVELS
RELATIVE ABUNDANCE OF SHELL IN MIDDEN
0
1
A1
CALICHE LAYERS
A2
A3
B
C
SOFT DARK SOIL, CALICHE CEMENTATION INCREASING DOWNWARD
DARK SOIL, CALICHE CEMENTED
YELLOW SAND
CLAY, IRON-CEMENTED SAND
SANDSTONE, EOCENE ROSE CANYON FM

FIGURE 3: Schematic Soil Profile and Vertical Distribution of Artifacts and Shell

(870)

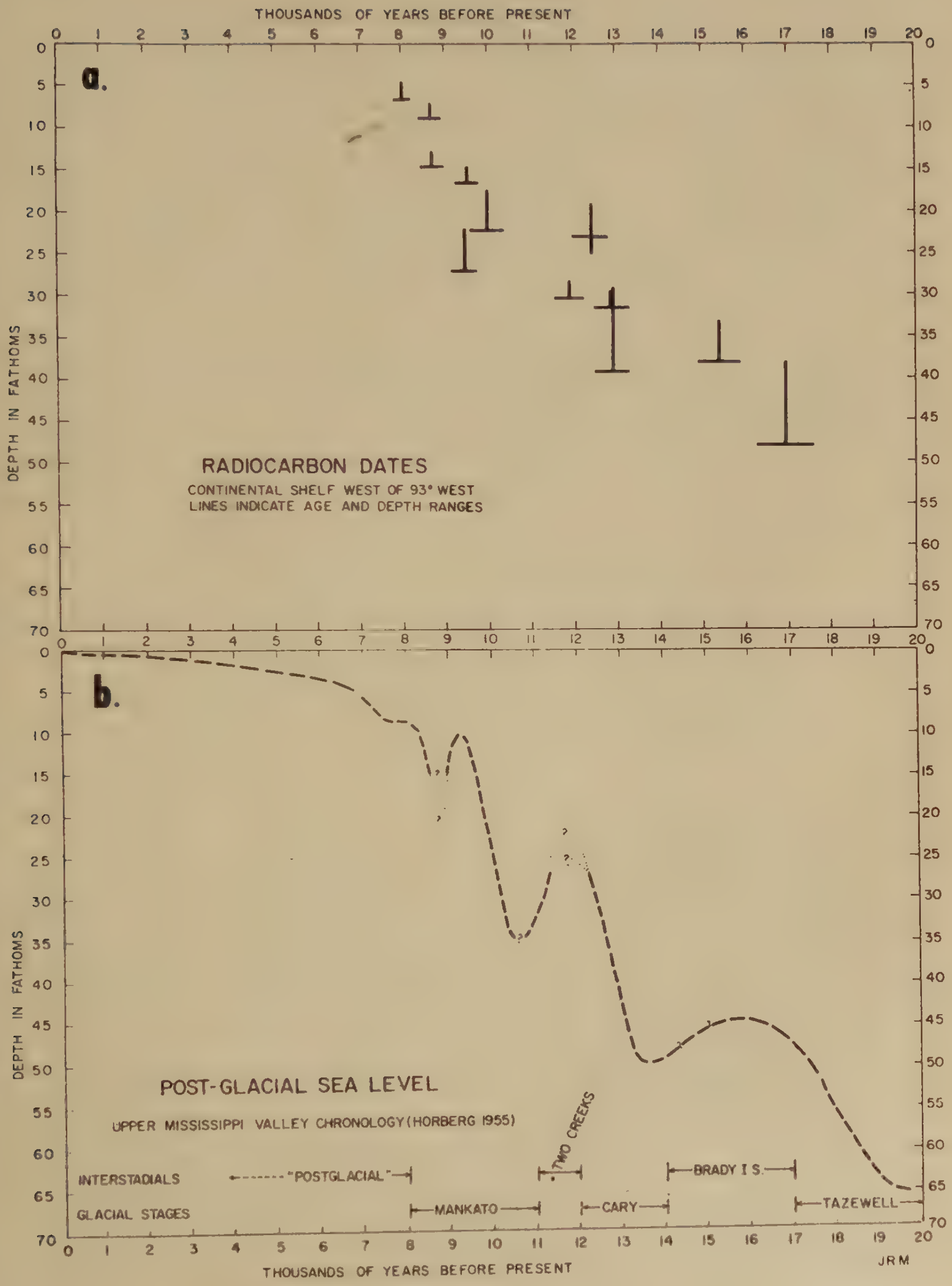


FIGURE 4: Post-Glacial Sea Level Changes

(872)

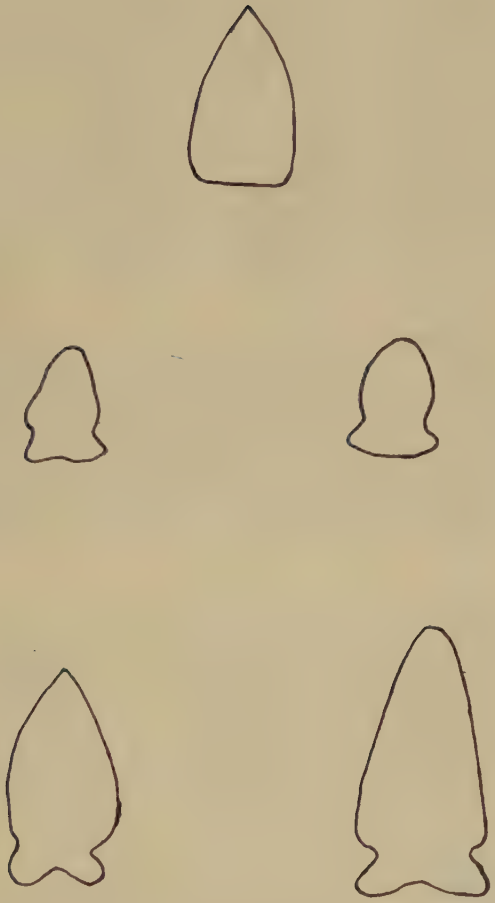


FIGURE 5: Projectile Points from Sorrento Valley Site

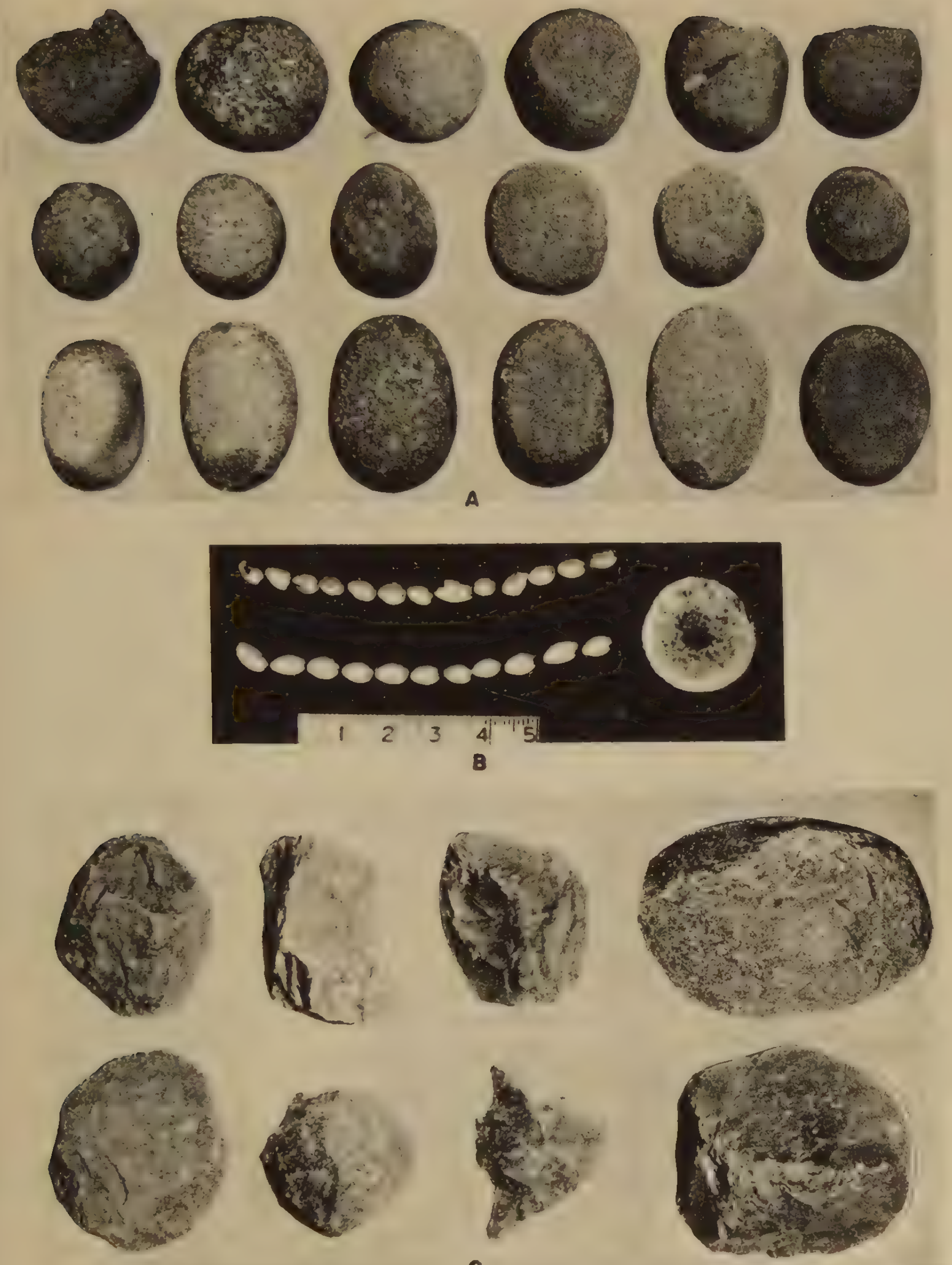


PLATE I: Manos, Shell Beads and Flaked Tools from Scripps Estates Site I

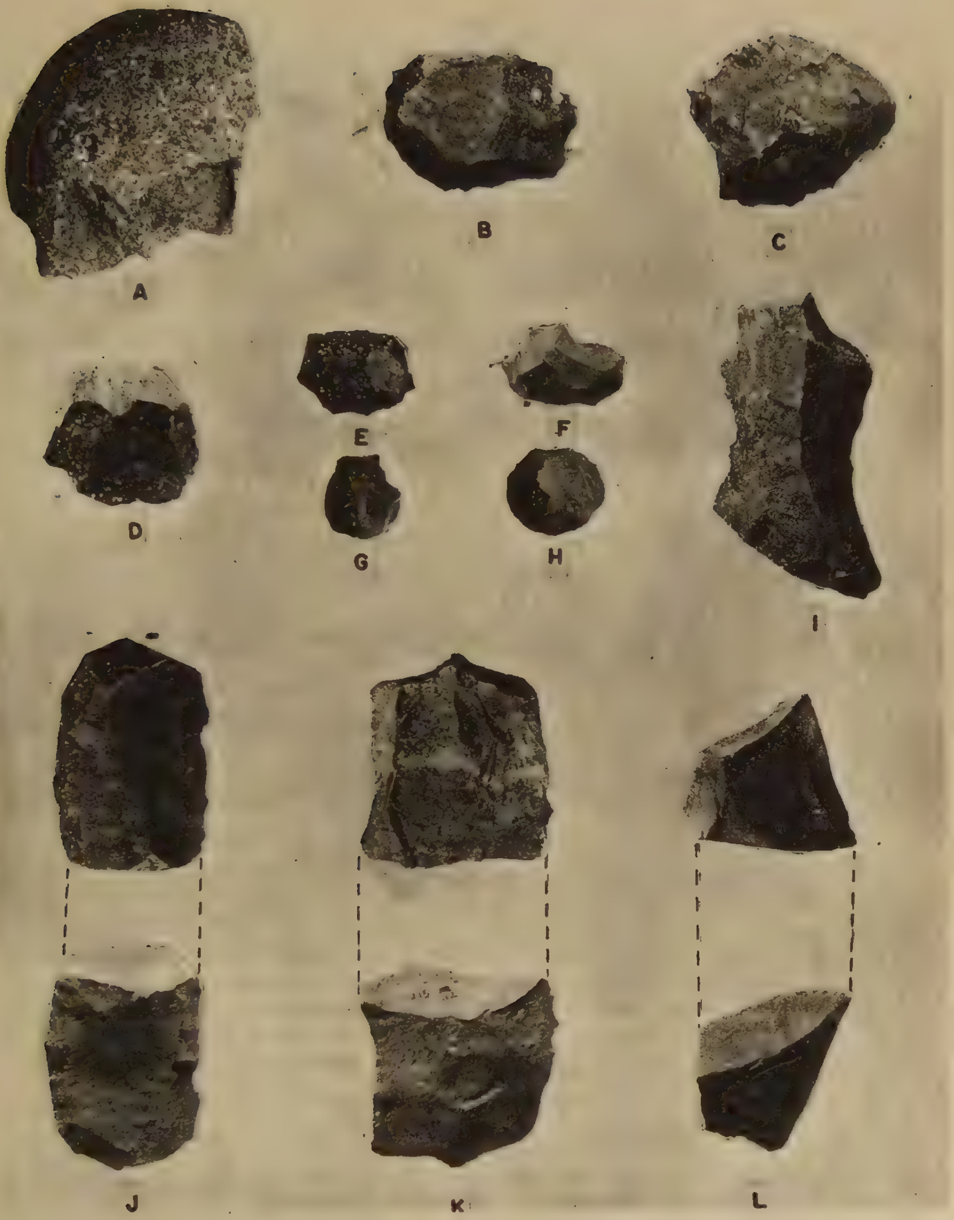

A
B
C
D
E
F
G
H
I
J
K
L

PLATE 2: Scrapers from Scripps Estates Site I

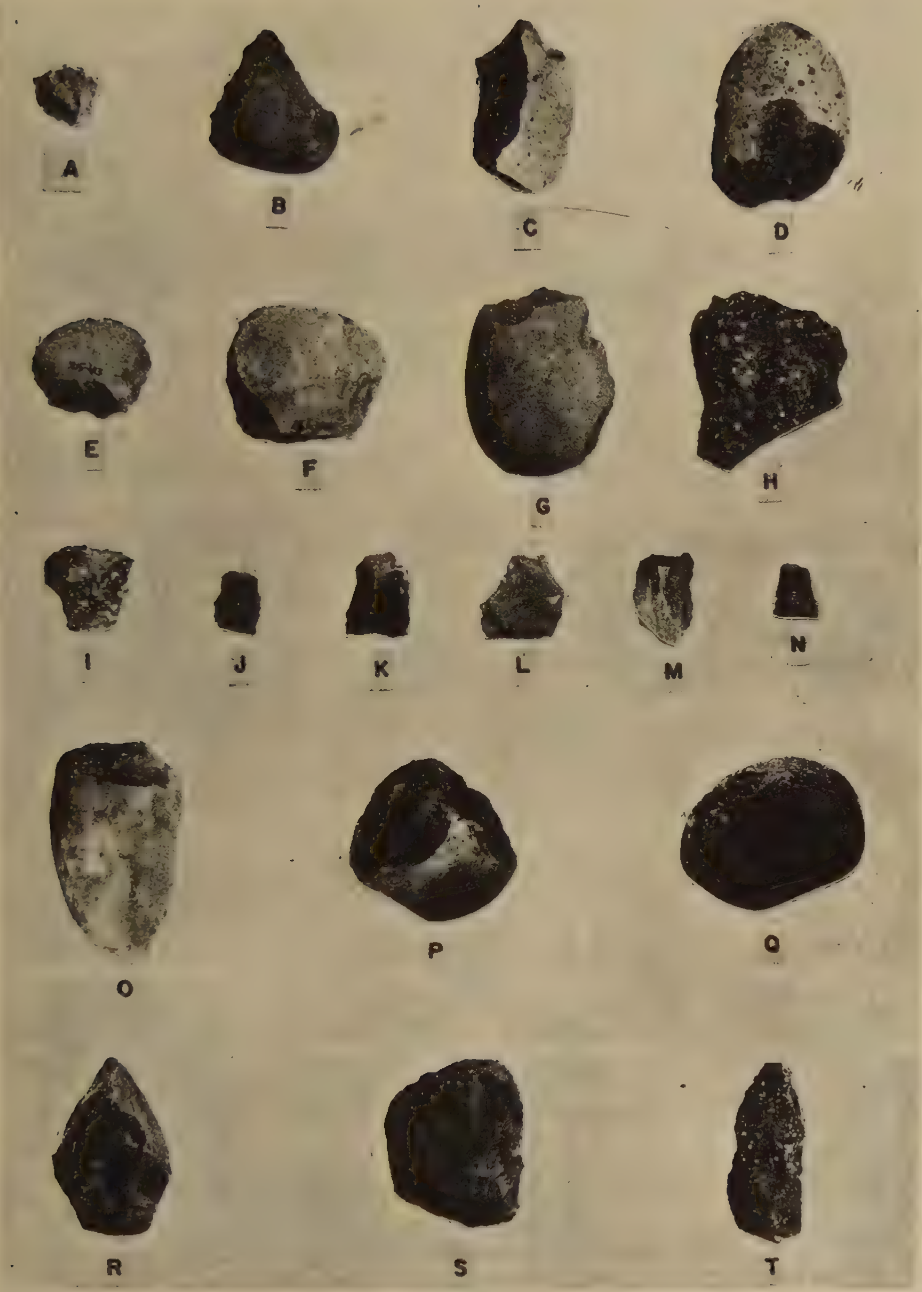

A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T

PLATE 3: Scrapers, Choppers and Pick from Scripps Estates Site I

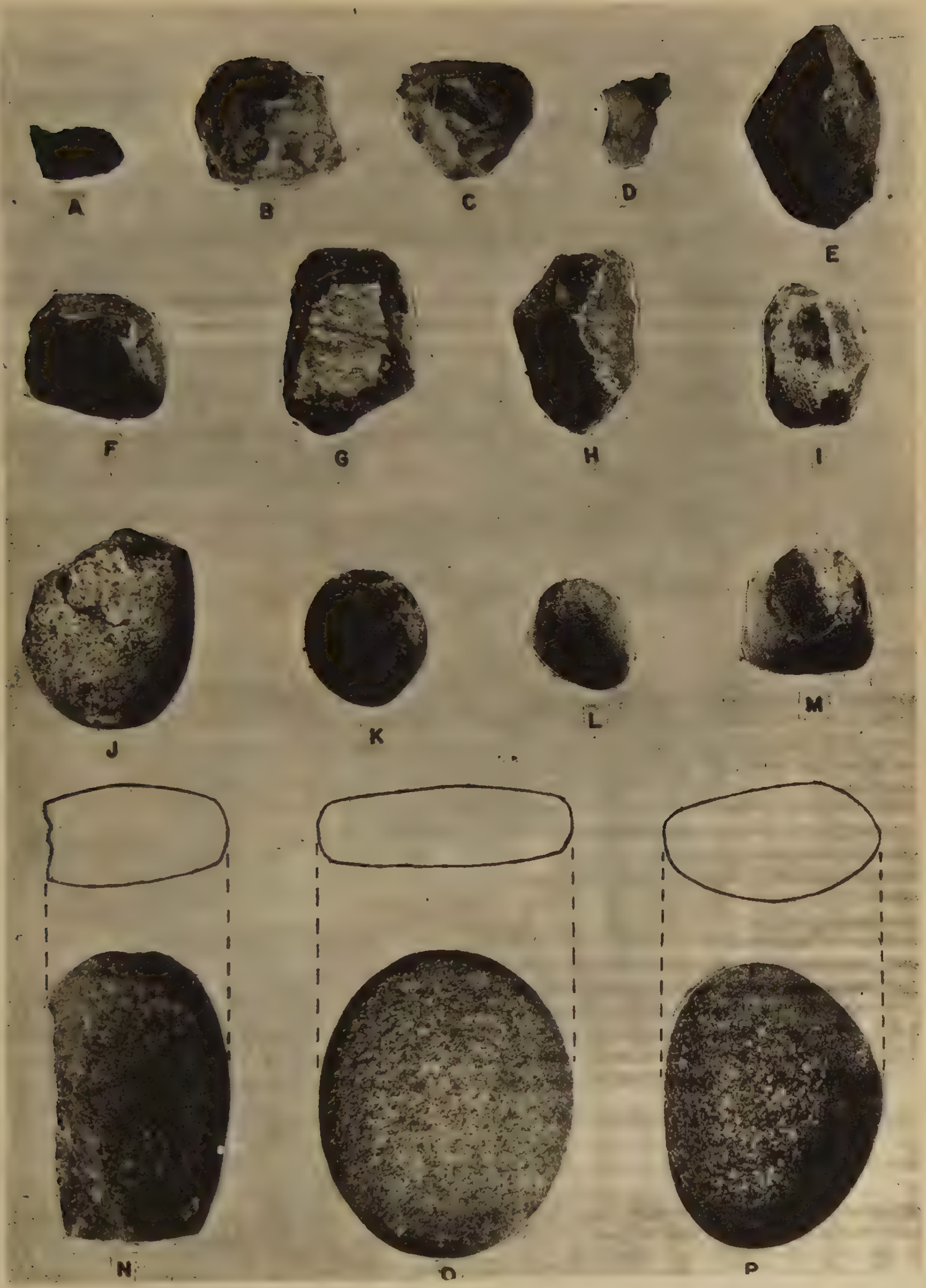

A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P

PLATE 4: Crescent, Cores, Hammerstones and Manos from Scripps Estates Site I

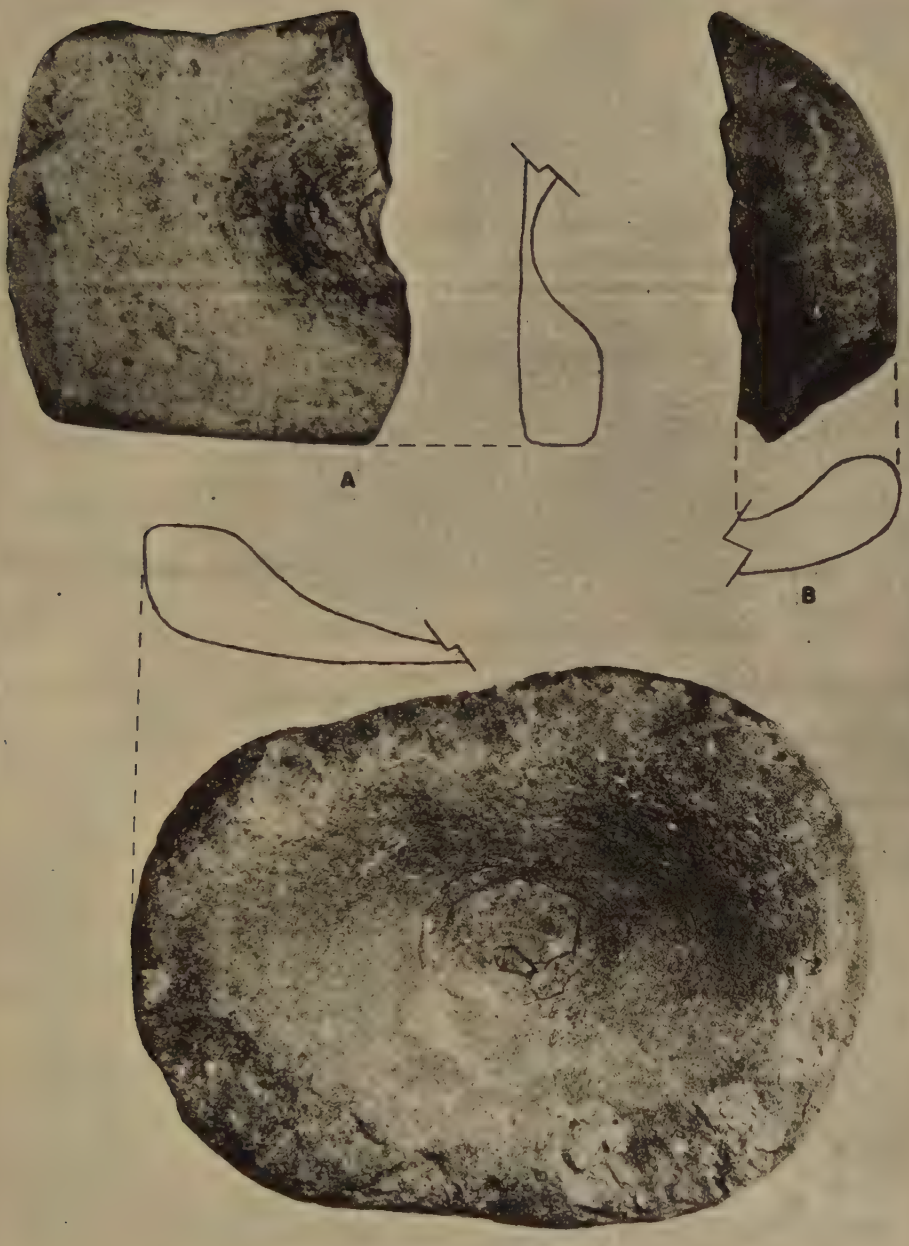


PLATE 5: Metates from Scripps Estates Site I

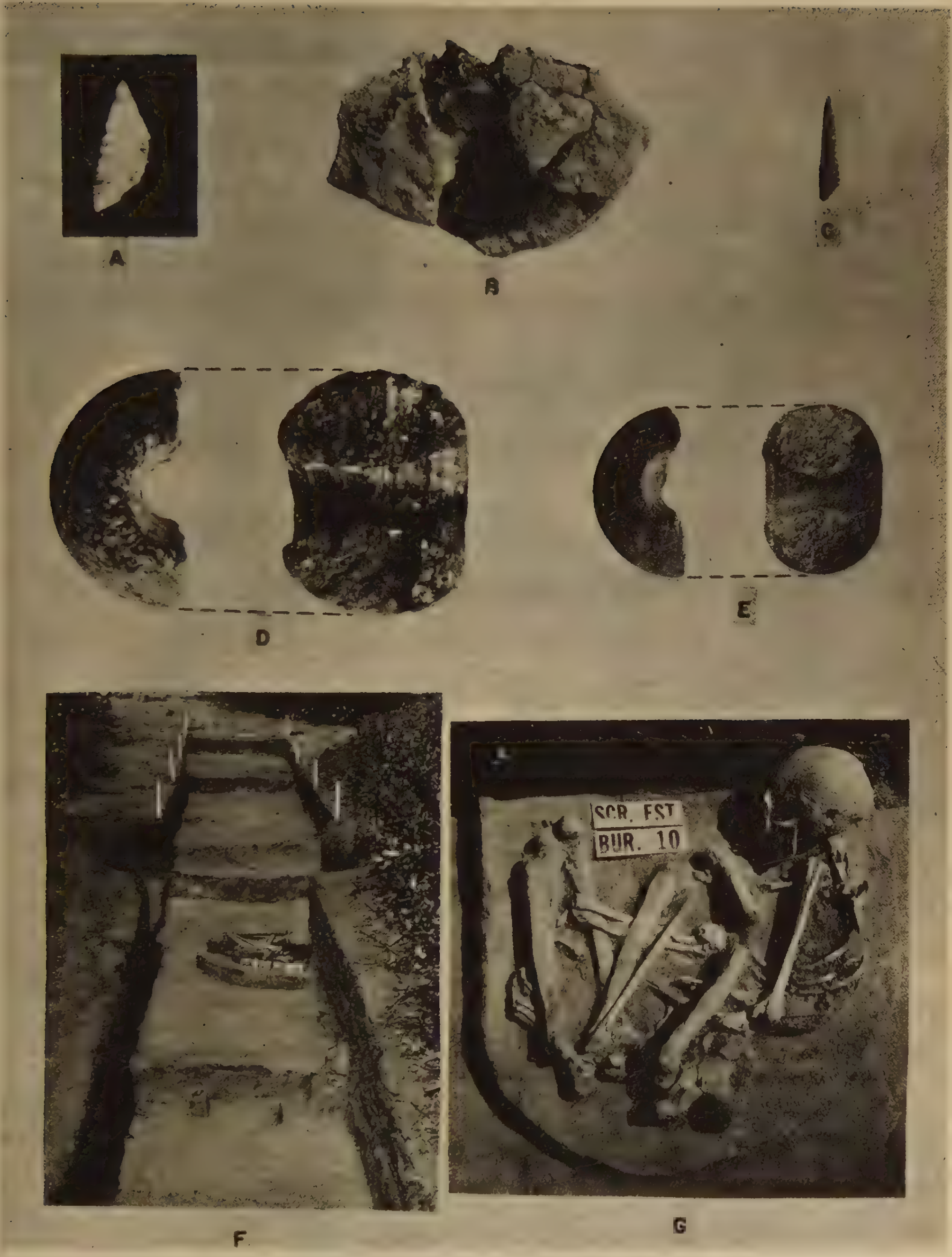

A
B
C
D
E
SCR. EST
BUR. 10
F
G

PLATE 6: Miscellaneous Artifacts, Test Trench I and Burial 10 from Scripps Estates Site I

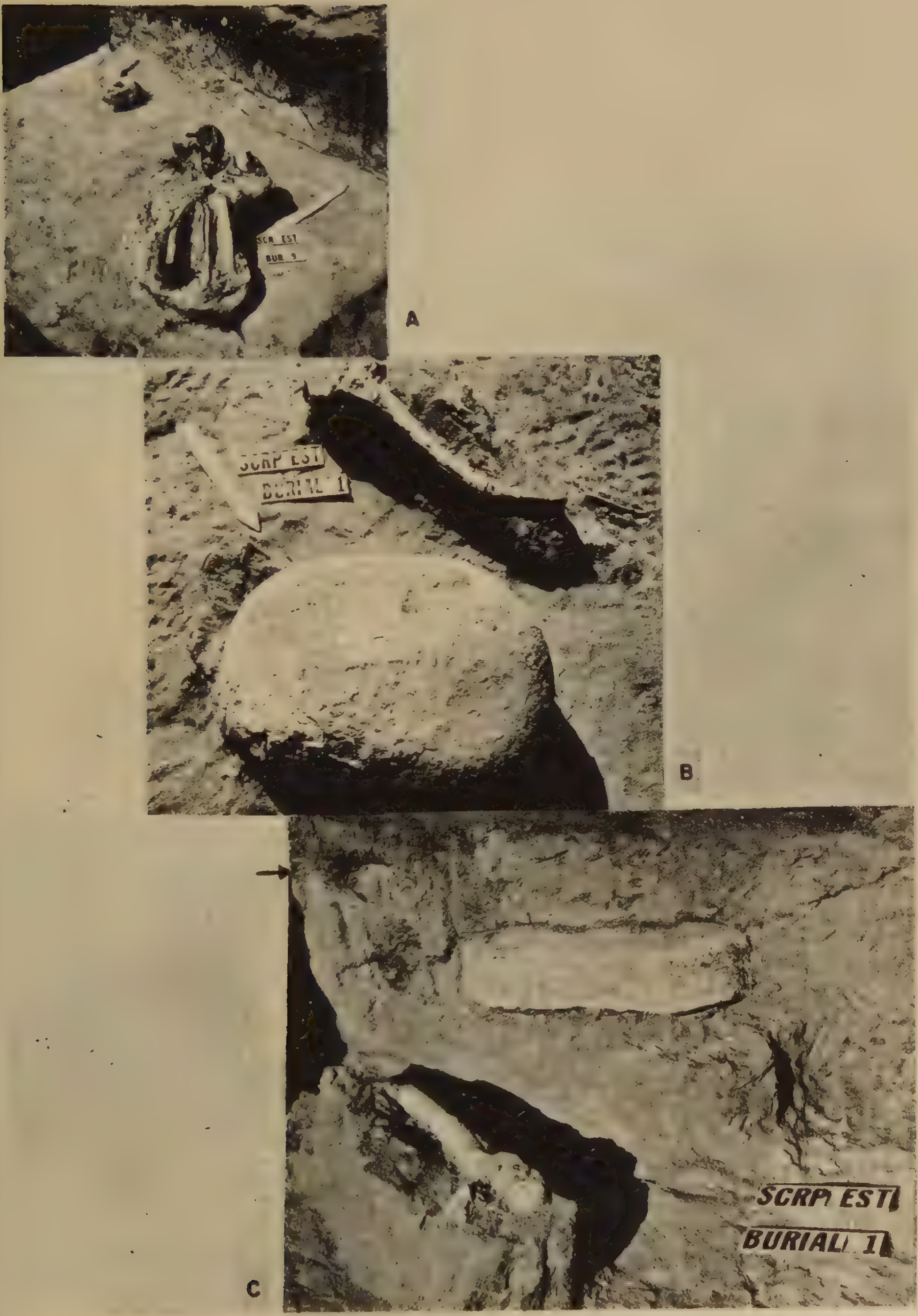

SCR EST
BUR 9
A
SCRP EST
BURIAL 1
B
SCRP EST
BURIAL 1
C

PLATE 7: Burials 9 and I from Scripps Estates Site I

(888)

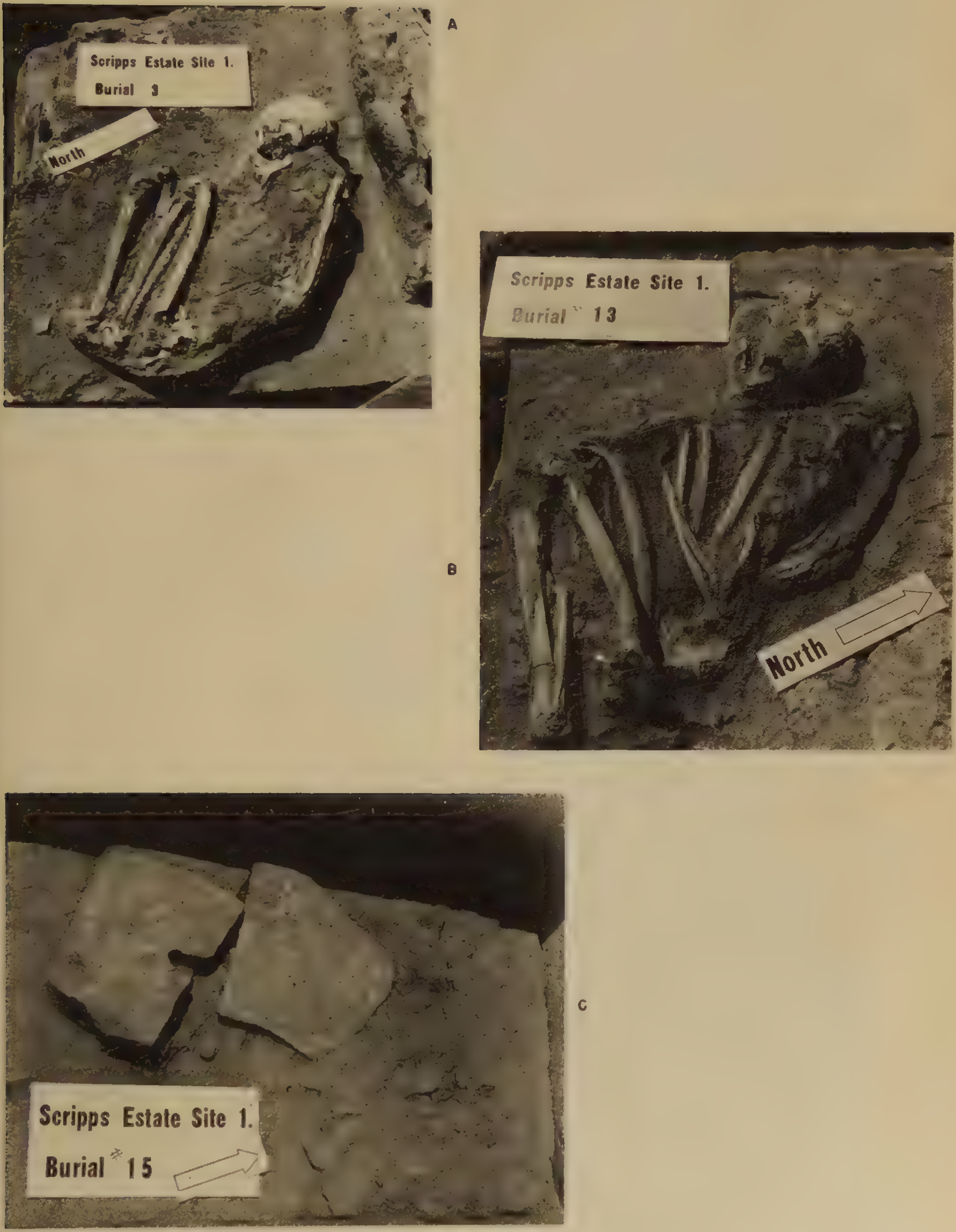

A
Scripps Estate Site 1.
Burial 3
North
B
Scripps Estate Site 1.
Burial " 13
North
C
Scripps Estate Site 1.
Burial # 15

PLATE 8: Burials 3, 13 and 15 at Scripps Estates Site I

Short Notes

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, PP. 1549–1552, 1 FIG. DECEMBER 1959

ANOMALOUS SEDIMENT DEPOSITION ON THE FLANK OF ENIWETOK ATOLL

BY M. N. BRAMLETTE, J. L. FAUGHN, AND R. J. HURLEY

Some short cores from the shelf at about 800–1000 fathoms on the southwest flank of Eniwetok Atoll (Fig. 1) penetrated Pliocene deposits with little to no later sediment cover. Of the 11 cores, 5 did not penetrate the upper Tertiary, although these were only 4 to 46 cm in length, and the Quaternary cover may thus be only slightly thicker than in the others. Where present, the thin veneer of recent or Quaternary sediment is strikingly different from the sediment of the upper Tertiary.

The Quaternary deposits include much coarse reef debris, particularly the fragments of algae such as *Halimeda* and other shallow-water material up to several millimeters in grain size, mixed with varying amounts of pelagic Foraminifera. The Pliocene sediments (one may be upper Miocene) are pure pelagic deposits of much finer grain size, consisting of coccoliths and pelagic Foraminifera with no admixture of reef material.

Bottom photographs show areas of well-developed ripple marks in coarse sediment (C. J. Shipek, manuscript) apparently formed only in the areas with the veneer of post-Tertiary coarse sediments. Evidently this shelf is now an area of agitated water which has permitted only a little and localized accumulation of the coarser sediments during Quarternary time. The marked contrast with the upper Tertiary fine-grained pelagic sediments (without reef material) is significant. The Tertiary sediments must have accumulated under topographic conditions rather similar to those of the present, as drilling has shown typical reef material from the surface of the atoll down into similar Tertiary reef deposits. The top of the Tertiary was not determined in the boring but was evidently much above the 1-mile depth of this shelf, as Miocene fossils were encountered at 620 feet (Ladd *et al.*, 1953, p. 2272). The near-surface reef material supplied through surface-wave action, perhaps most actively during glacial changes in sea level, is easily carried down the steep flanks of the atoll. Such debris, although presumably supplied at the base of the steep slope during the Tertiary also, evidently was not carried out over most of the shelf during that time, even though these Tertiary shelf deposits must have been almost as near the steep slope of the atoll. The continued growth of the reef during the Tertiary does not allow for any period of different conditions such as a subsidence to much greater depths below the water surface.

Much less water agitation on the shelf during the late Tertiary is also indicated by the great abundance of the tiny coccoliths in the Tertiary deposits. The coccoliths range from about 2 to about 10 microns, yet they form about half these unsorted pelagic deposits. Fine-grained constituents have been winnowed out and form a negligible part of the recent deposits.

The upper Tertiary sediments have been somewhat indurated by secondary calcite cementation, evidently related to the considerable corrosion and secondary growth evident on the coccoliths. A brown impregnation at the top and extending down as mottling for a few centimeters is also usual in the Tertiary sediment of the cores. This seems to consist of iron and manganese oxides and adds somewhat to the induration. This slight, but obvious, lithification appears to be sufficient to prevent winnowing or erosion of the very fine chalky Pliocene sediment under the present conditions of strong water motion that now permits deposition of only a little coarse sand, granule, and gravel-size material. This coarser material with reef debris shows no induration, and stable accumulation in the patchy, thin veneer may be negligible, as much of this is doubtless being shifted across the shelf to deeper water.

The effects of strong water motion on this Quaternary deposition off Eniwetok is thus especially clear. It also seems a clear, although

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not unique, example of a marked contrast with the pre-Quaternary deposits, both accumulated here under comparable topographic relations. Some limitation on any possible changes in water depth here is also indicated by the record of continued coral-reef growth.

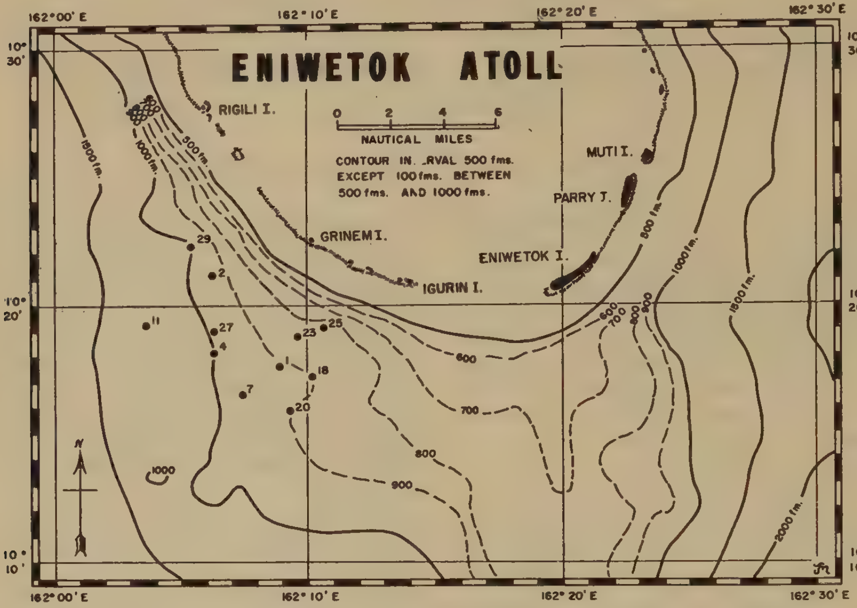

Figure 1.—Location of Cores on Shelf on the Southwest Flank of Eniwetok Atoll

Many photographs of ripple marks are now available to supplement other good evidence of considerable bottom-water motion in the modern deposits on guyots, the Mid-Atlantic Ridge, and other topographic highs. Deep currents of adequate strength are now being recognized in the Atlantic, although their pattern and cause are not yet clear (Swallow and Worthington, 1957, p. 1183–1184).

Water motion at a depth of about 1 mile on the terrace bottom seems, however, to have been of no more importance in the late Tertiary sedimentation than was once thought usual in the modern oceans below depths influenced by waves and currents known at the surface. The marked difference in such paleo-oceanographic conditions would not seem probable, although some conditions of the Quaternary oceans, as of the continents, may be rather abnormal as compared with those during much of the earth's history. Strength and pattern of some surface currents may have been modified during the ice age, and perhaps the deeper circulation was equally or more greatly modified by the polar ice caps. Such difference in the strength of deep-water motion is suggested by some other occurrences, showing a similar contrast in character between the Quaternary deposits and those of several ages within the Tertiary. These other occurrences, however, have not had the additional evidence indicated by the relations to a drilled coral reef, and the debris from it.

Prior to the recent recognition of the probable strength of deep currents, other possibilities for adequate water motion to produce the observed results included the occasional tsunamis. With this hypothesis, however, the described difference in the sediment records would imply the improbable condition that tsunamis were much less important in pre-Quaternary time.

Evidence for the age assignments will not be presented here but is based largely on the distinctive assemblages of coccoliths, including discoasters and related forms. Differences between the pelagic assemblages of Quaternary and Pliocene Foraminifera are not great and seem to be of little age significance, although the common occurrence of *Globigerinoides sacculifera fistulosa* (Schubert) in the Pliocene here and elsewhere may be significant, as the typical form of the subspecies has not been found in post-Tertiary deposits. The specimen figured in Cushman's textbook (Foraminifera) is designated as Recent, but neither this specimen nor records of it can now be found, and it is not recorded in his publications on Recent Foraminifera. Microfossils from Tertiary occurring at the ocean's bottom surface and reworked from these "outcrops" are more common than formerly recognized, however, and such a specimen may thus have been found in an otherwise Recent assemblage. Core 20 is evidently older than the others assigned to the Pliocene, as indicated by both the coccoliths and Foraminifera, and may prove to be of late Miocene age, if a differentiation of this from early Pliocene is possible.

This work represents results of research supported, in part, by the Office of Naval Research.

References Cited

Ladd, H. S., Ingerson, E., Townsend, R. C., Russell, M., and Stephenson, H. K., 1953, Drilling on Eniwetok Atoll, Marshall Islands: Am. Assoc. Petroleum Geologists Bull., vol. 37, p. 2257–2280

Swallow, J. C., and Worthington, L. V., 1957, Measurement of deep currents in the western North Atlantic: Nature, vol. 179, p. 1183–1184

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Brief Notes on Core Samples

(*Globigerina* sand is used for sand-sized sediments composed largely of *Globigerina* and other pelagic Foraminifera, and "ooze" for the very fine-grained sediments. High calcium-carbonate content indicated by four analyses seem representative.)

Core No.	*Length (cm)*	
1	0–21	*Globigerina* sand with some sand-size reef debris (Quaternary)
2	0–20	Reef debris of coarse sand to granule size and *Globigerina* sand (Quaternary)
4	0–61	Slightly indurated *Globigerina*-coccolith "ooze", with brown crust in top 3 cm and decreasing brown mottling down to 10 cm (Pliocene)
7	0–4	*Globigerina* sand with reef debris up to coarse sand size (Quaternary)
11	0–2	Brown volcanic sand with calcite cementation of upper 1 cm. No Foraminifera nor reef debris (age?)
18	0–5	*Globigerina* sand with some reef debris of medium to coarse sand size (Quaternary)
	5–61	Slightly indurated *Globigerina*-coccolith "ooze" with faint brown mottling near top (Pliocene)
20	0–13	Slightly indurated *Globigerina*-coccolith "ooze" ($CaCO_3$ = 95 per cent at 12 cm) with brown crust at top and brown mottling decreasing downward (lower Pliocene or upper Miocene).
23	0–12	*Globigerina* sand with some reef debris of coarse sand size (Quaternary).
	12–66	Slightly indurated *Globigerina*-coccolith "ooze" ($CaCO_3$ = 96 per cent at 30 cm) with brown mottling decreasing downward from 12 to 25 cm (Pliocene)
25	0–46	Reef debris and *Globigerina* sand, with coarser debris up to 4 mm at 4–8 cm and at 15 cm ($CaCO_3$ = 93 per cent at 20 cm) (Quaternary).
27	0–12	*Globigerina* sand with some reef debris (Quaternary)
	12–28	Slightly indurated *Globigerina*-coccolith "ooze", with brown crust at top and brown mottling decreasing downward (Pliocene)
29	0–10	Reef debris of coarse sand size and *Globigerina* sand (Quaternary).

(894)

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THE FOOD OF THE LARVAE OF THE NORTHERN ANCHOVY *ENGRAULIS MORDAX*

EL ALIMENTO DE LAS LARVAS DE LA ANCHOA NORTEÑA *ENGRAULIS MORDAX*

by — por

LEO BERNER, JR.

La Jolla, California
1959

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THE FOOD OF THE LARVAE OF THE NORTHERN ANCHOVY *ENGRAULIS MORDAX*[1][2]

by

Leo Berner, Jr.

Hitherto the only investigation dealing with the food and feeding of the larvae of the northern anchovy, *Engraulis mordax* Girard, was that of Arthur (1956). His main consideration was, however, with the Pacific sardine, *Sardinops caerulea* (Girard), and his work on the anchovy can only be considered preliminary. The present investigation is a continuation of Arthur's work on the food of the larval northern anchovy.

The larvae used in this study (Table 3) were supplied by Dr. E. H. Ahlstrom of the South Pacific Fisheries Investigations of the U.S. Fish and Wildlife Service. They were collected in 1954 by routine plankton tows made by the California Cooperative Oceanic Fisheries Investigations off the coasts of California and Baja California (Figures 1-3). The author also wishes to thank Drs. Martin W. Johnson and Carl L. Hubbs for critically reading the manuscript and offering many helpful suggestions and Mrs. Alice Theilacker who prepared the figures.

METHOD

The method of examining the larvae was similar to that used by Arthur. The larvae were removed from their preserving fluid, 5% formalin, and placed in 95% glycerine. This had several advantages. The larvae were cleared so that most food particles could be located in the gut without dissection. In addition, the larvae were made more pliable and less prone to breakage during dissection and the greater viscosity of the glycerine dampened movement and thus facilitated dissection.

After clearing for at least 24 hours, the larvae were examined through a low-powered microscope for food particles in the gut. As in all clupeoid larvae, the gut of the anchovy is suspended below the body musculature so that it is visible along its entire length, except for a short portion obscured by the liver. Those larvae found to contain food, or suspected of containing food, were placed on a microscope slide for further examination at higher magnification. Many food particles could be identified and measured in place; others were dissected out for more detailed study.

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[1] Contribution from the Scripps Institution of Oceanography, New Series. 1121

[2] This work was carried out while the author was employed by the U.S. Department of the Interior, Fish and Wildlife Service, Bureau of Commercial Fisheries, La Jolla, California.

FEEDING

Soleim (1942) observed that food ingested by herring larvae passed very quickly to the posterior part of the intestine. Food particles ingested by the anchovy apparently pass down the oesophagus rapidly; in this investigation no larvae were found with food in that organ. Preliminary investigation suggested that food might be present in localized swellings observed along the course of the oesophagi of many larvae. Careful dissection of a number of these swollen areas indicated that they contained no food material and it is assumed that they represent gulps of water taken in during the death throes of the larvae. A lesser number of larvae were found with large distended bubble-like areas in the gut. Examination of these areas never disclosed food particles.

Material in the intestine usually was readily visible through the surrounding tissue although some well-digested particles were found only by dissecting small distended areas in the gut. In some larvae longer than 12 mm. the gut wall in the vicinity of food particles was poorly preserved although otherwise these larvae were in excellent condition. It appeared that the penetration of the formalin had been slow and that the digestive enzymes had destroyed the gut from within.

SIZE OF FOOD

Arthur (1956) found that anchovy larvae ingested food covering a greater size range than did sardine larvae. My data indicate an even wider range of food size for the anchovy larvae taken in 1954 than for those examined by Arthur (Table 1). These differences cannot be related to seasonal effects but the available food may have been quite different in 1951-52.

There is a trend toward larger food as the larvae get longer (Table 2) but this trend is less marked than in the sardine. Figure 4 shows the distribution of food particle size, less than 300μ, in larvae between 2.5 and 10 mm. in length. There were only four food items longer than 300μ found.

COMPOSITION OF DIET

The actual composition of the food material in the anchovy larvae collected in 1954 differed strikingly from that found by Arthur (Table 2). The 1954 larvae, instead of becoming less euryphagous with size, continued to eat a large variety of material. The larvae longer than 7 mm. actually ate the greatest variety of food. Crustacea, mainly copepods in various developmental stages, comprised the major food item of all larval groups.

The large percentage of dinoflagellates in larvae longer than 7 mm.

resulted almost entirely from the data from one station. One 10 mm. anchovy from this station contained 21 dinoflagellates, the largest number of food particles found in any larva.

INCIDENCE OF FEEDING

The greatest percentage of feeding larvae was found in the smaller sizes with the largest group at a length of 3.75 mm. (Figure 5). In the smallest sizes, 2.5 and 3.0 mm., the proportion of feeding larvae drops abruptly because of the predominance of non-feeding yolk sac larvae. No anchovy with unpigmented eyes contained food. Loss of yolk and development of pigment in the eyes occur simultaneously. There is also a marked drop in the percentages of feeding larvae in the larger sizes, as represented by the samples examined. Food is rarely found in larvae longer than 10 mm. Between 4.5 and 9.5 mm. the drop in percentages of feeding larvae very closely parallels the drop in the percentages of total larvae in each size group. Beyond 9.5 mm. the percentage of feeding larvae drops to a very low level.

Lebour (1918, 1919, 1920, 1921), who discussed the food of many larval fishes, stated (1921) "... some thousands of young Clupeoids were examined, with the result that by far the larger proportion of the post-larvae were found empty". Other investigations of the feeding of clupeoid larvae have disclosed the same low feeding incidence. The overall feeding incidence indicated by data from the 1954 cruises was very low, 211 feeding larvae were found in a total of 13,620 potentially feeding larvae i.e. yolk sac larvae were not included. The feeding incidence for any cruise did not differ appreciably from the over-all incidence of 1.5%. However, if day and night feeding incidence are compared, the day incidence is seen to be at least 10 times that for the night (Table 4). If "day" is defined as the period from sunrise to sunset, 81.5% of the feeding larvae were taken in daytime plankton hauls. If, however, 45 minutes are allowed for twilight, 95.3% of the feeding larvae were caught during daylight hours. Only 32.7% of the total post-yolk-sac larvae were taken in daylight and twilight hauls, thus 95.3% of feeding larvae are found in only 32.7% of the potentially feeding larvae. This indicates a rather strong reliance on vision in the feeding of the anchovy larvae.

In examining the charts (Figures 1-3) showing the locations where anchovy larvae were taken during the three cruises under discussion, it may be noted that the stations where feeding occurred are not distributed over the whole region but tend to occur in definite areas. These regions, respectively south of Pt. Conception and Pt. Eugenia, are areas of concentrations of organisms on which fish larvae feed (Arthur, 1956).

PHYSICAL CONDITION OF LARVAE

Throughout this investigation the number of poorly preserved larvae found in the samples was striking. Many had lost their eyes and were quite flaccid; in some the liver was almost completely consumed. It was impossible to determine positively whether this poor condition was due to damage while the larvae were being captured alive, or to poor preservation and handling after capture, or the circumstance that the larvae were actually dead or dying when captured. Other investigators have also found presumably dead larvae in their samples. Soleim (1942), in his work on the herring, *Clupea harengus,* reported larvae that were presumably dead when taken in plankton hauls. Marr (1956:167-168) suggests this may be the report of an artifact brought about by poor washing of the net; he does, however, list some other examples of larvae which were dead when caught. Arthur (1956) reported a considerable number of sardine larvae in poor condition and assumed that a large percentage of them might have been dead at the time of capture. He (1956:105) tabulated the morphological differences between well and poorly preserved larvae, as determined from a detailed examination of a large group of larvae. It seems probable that a significant number of larvae captured by our routine plankton hauls and examined in this work, were either dead or dying at the time. The appearance of the liver may be one of the best indicators of the condition of the larvae at the moment of capture. In poorly preserved larvae a large, intact liver suggests a larva that was injured in capture or preservation, whereas a nearly consumed liver suggests a larva which was starving or moribund at the time of capture.

Anchovy larvae longer than 15 mm. were usually well preserved, in spite of their extremely low feeding incidence Most of these larger larvae were caught at night when, on the basis of our data, they would be least expected to contain food. A plausible explanation of this phenomenon is that the larger larvae are able to avoid the net during daylight when they are feeding and are only caught at night when they are not feeding. The undersampling of larger sardine larvae during daylight hours has been examined by Ahlstrom (1954:129-130); these data are also applicable to the anchovy.

DISCUSSION

The low feeding incidence found in clupeoid larvae has brought about considerable speculation. In discussing the reason for the lack of food in young clupeoids, Lebour (1921:458) suggests a probable reason for this apparent absence of food in the transparent stages is that the food must be quickly digested because its presence in the gut makes the larvae so conspicuous. Thus food is taken only at long intervals and rapidly passed through the gut. It would follow, under these circumstances, that fish containing food would only occasionally be caught. Arthur (1956) set forth two additional possibilities: the first, suggested by Dr. Carl L. Hubbs, is that the gelatinous, watery leptocephalus type body of the clupeoid larvae may require less nourishment per unit volume than larvae with a more substantial body. The second, which he discussed at length, but applied only to sardines, is that healthy larvae are able to escape the net and those caught represent disproportionate percentages of sick or dying larvae. My observation that in the larvae examined there did appear to be a disproportionate number of very poorly preserved "dead" individuals fits this alternative hypothesis. It is probable that all these factors operate to some degree, but it is not possible to give estimates of their relative importance.

Morris (1955) suggested that marine fish may actually gain part of their nutrition from "dissolved" organic matter and outlined a mechanism for its use, and in support of this view wrote (p. 258) that: "Among a large number of larvae held in the laboratory, I have seen no indication that digestion proceeded at a very rapid rate nor has it appeared very complete". He unfortunately did not say what types of larvae he held, nor did he define "rapid". Later (1956) he lists the larvae held and the lengths of time he was able to hold them but adds nothing to the discussion of digestive rates or efficiency. In a personal communication to Arthur, he stated that anchovy larvae 30 to 40 mm. long, with empty guts, voided fecal material an hour to an hour and a quarter after the initial addition of food to the tank.

From our samples very little can be said about the speed of digestion. In two samples taken within 45 minutes after sunset, however, the food particles present were all in the posterior portions of the guts. Digestion of most material found in the anchovy guts was quite complete. Copepod nauplii could be identified only by the chitinous exoskeleton, which resembled a line drawing; all the internal material being digested away.

Whatever the explanation, all studies of the stomach contents of clupeoid larvae have indicated a very low incidence of feeding. The definitive test of any one or combination of the hypotheses set forth to explain this apparent lack of food cannot come from a study of preserved larvae, but must come from carefully controlled experiments with living specimens, under conditions simulating those that obtain in nature.

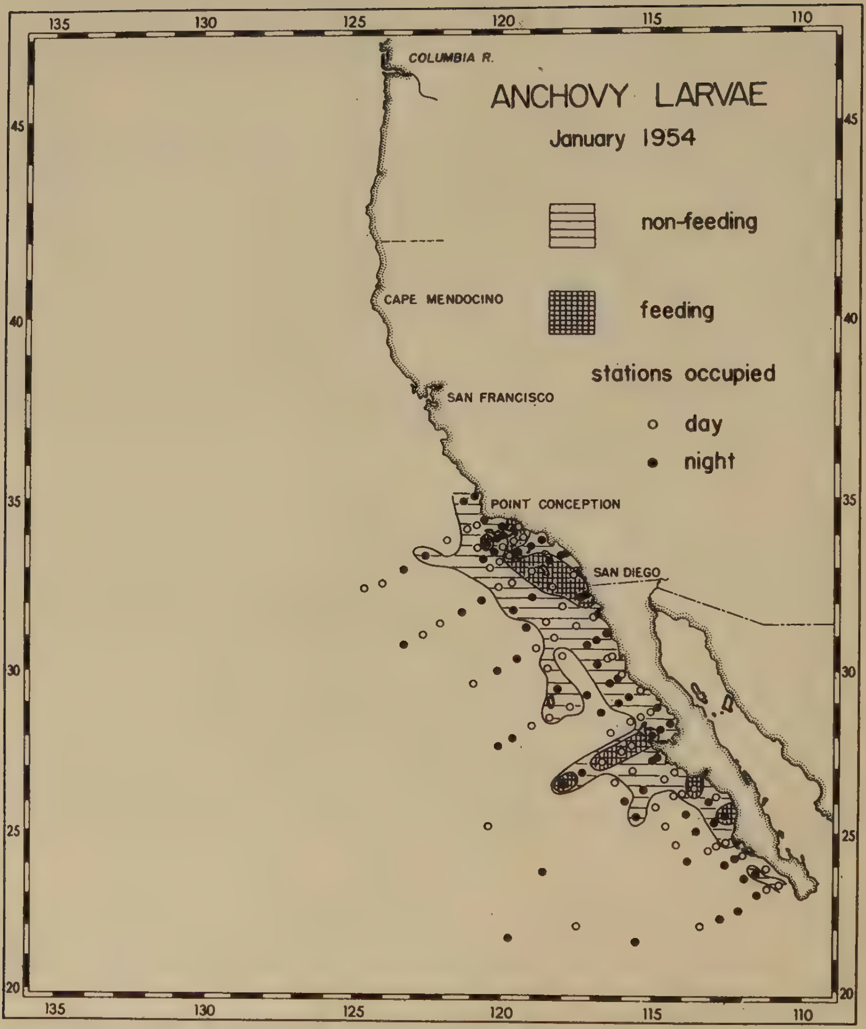
ANCHOVY LARVAE
January 1954
non-feeding
feeding
stations occupied
○ day
● night
COLUMBIA R.
CAPE MENDOCINO
SAN FRANCISCO
POINT CONCEPTION
SAN DIEGO
135
130
125
120
115
110
45
40
35
30
25
20

FIGURE 1. Distribution of feeding and non-feeding larvae during January 1954.

FIGURA 1. Distribución de larvas alimentándose y sin alimentarse, durante enero de 1954.

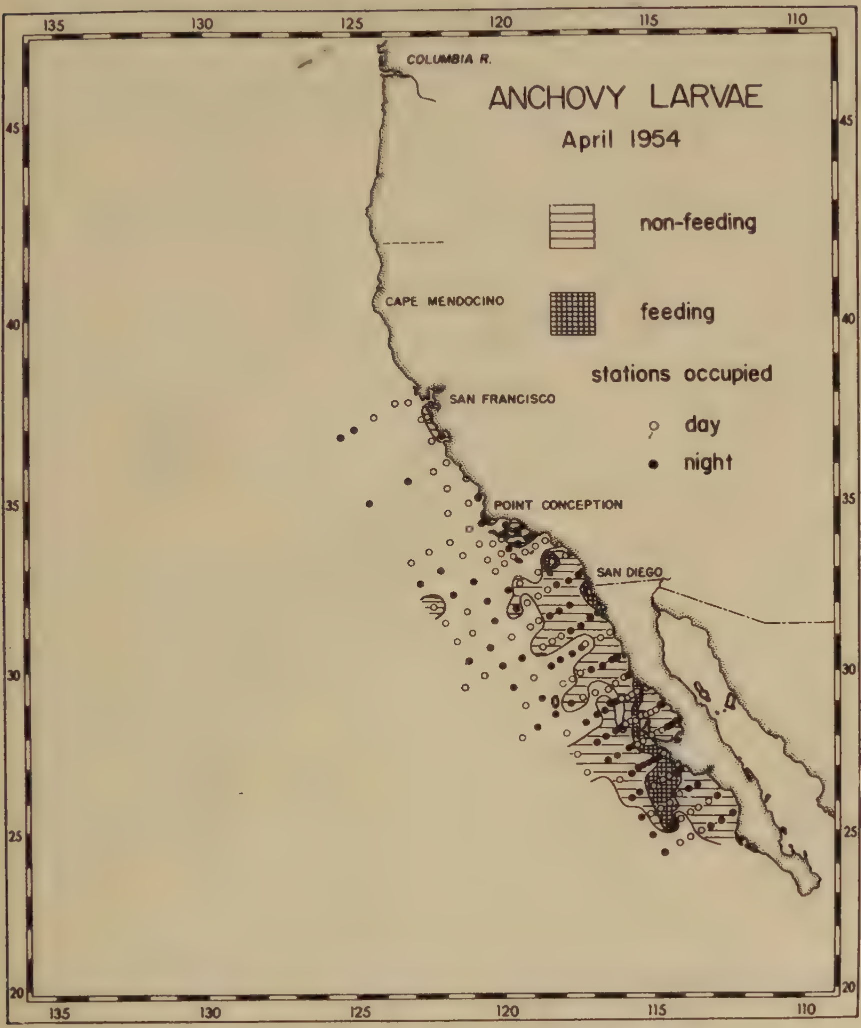
ANCHOVY LARVAE
April 1954
non-feeding
feeding
stations occupied
day
night
COLUMBIA R.
CAPE MENDOCINO
SAN FRANCISCO
POINT CONCEPTION
SAN DIEGO
135
130
125
120
115
110
45
40
35
30
25
20

FIGURE 2. Distribution of feeding and non-feeding larvae during April 1954.

FIGURA 2. Distribución de larvas alimentándose y sin alimentarse, durante abril de 1954.

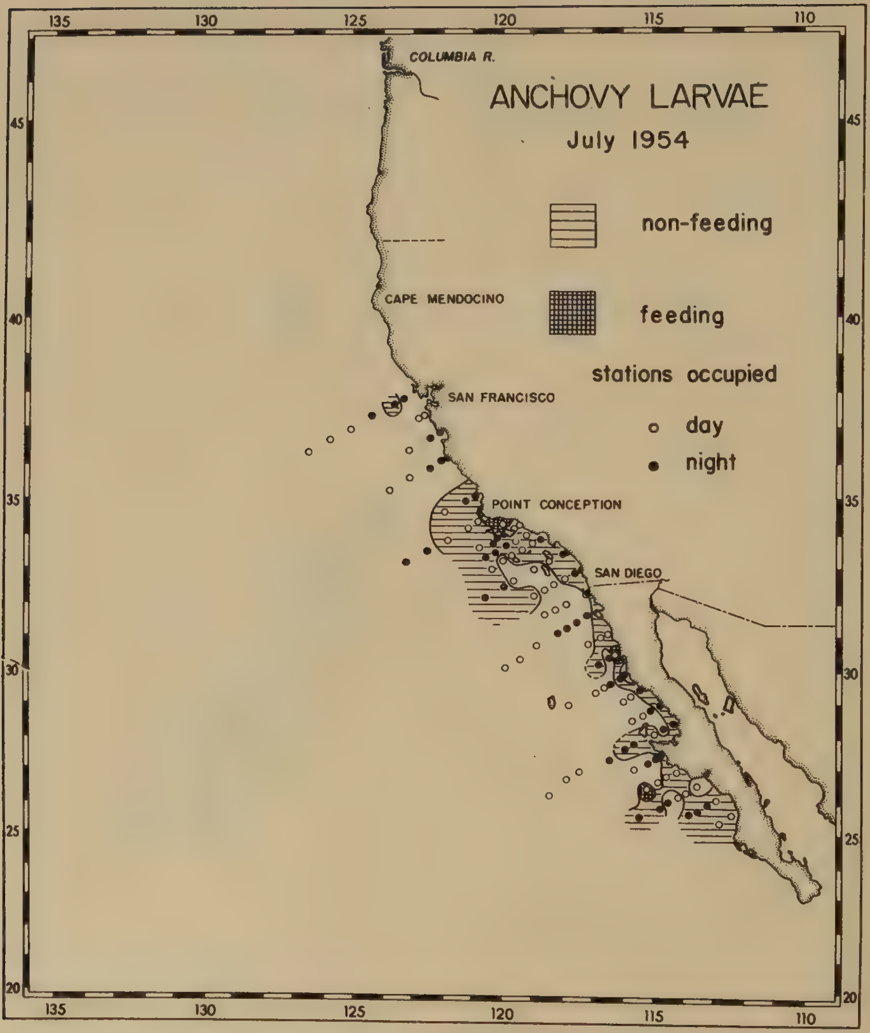
135
130
125
120
115
110
45
40
35
30
25
20
COLUMBIA R.
ANCHOVY LARVAE
July 1954
non-feeding
feeding
stations occupied
day
night
CAPE MENDOCINO
SAN FRANCISCO
POINT CONCEPTION
SAN DIEGO

FIGURE 3. Distribution of feeding and non-feeding larvae during July 1954.

FIGURA 3. Distribución de larvas alimentándose y sin alimentarse, durante julio de 1954.

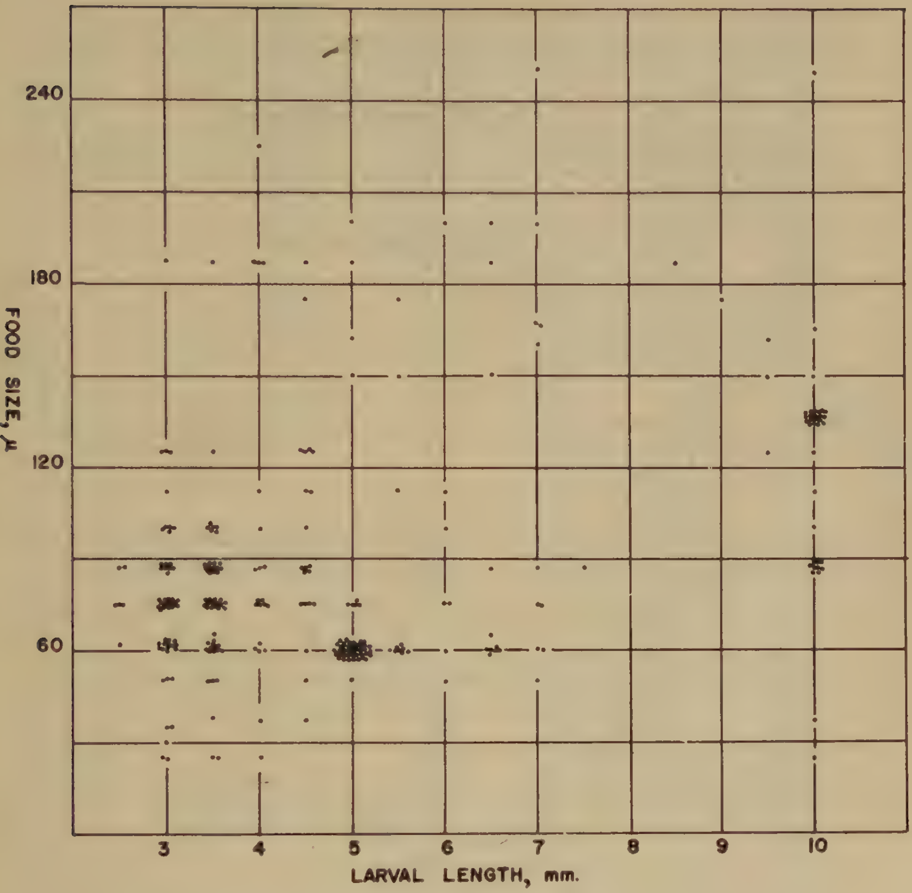

FIGURE 4. Comparison of food size and larval length.

FIGURA 4. Comparación del tamaño del alimento y de la longitud de las larvas.

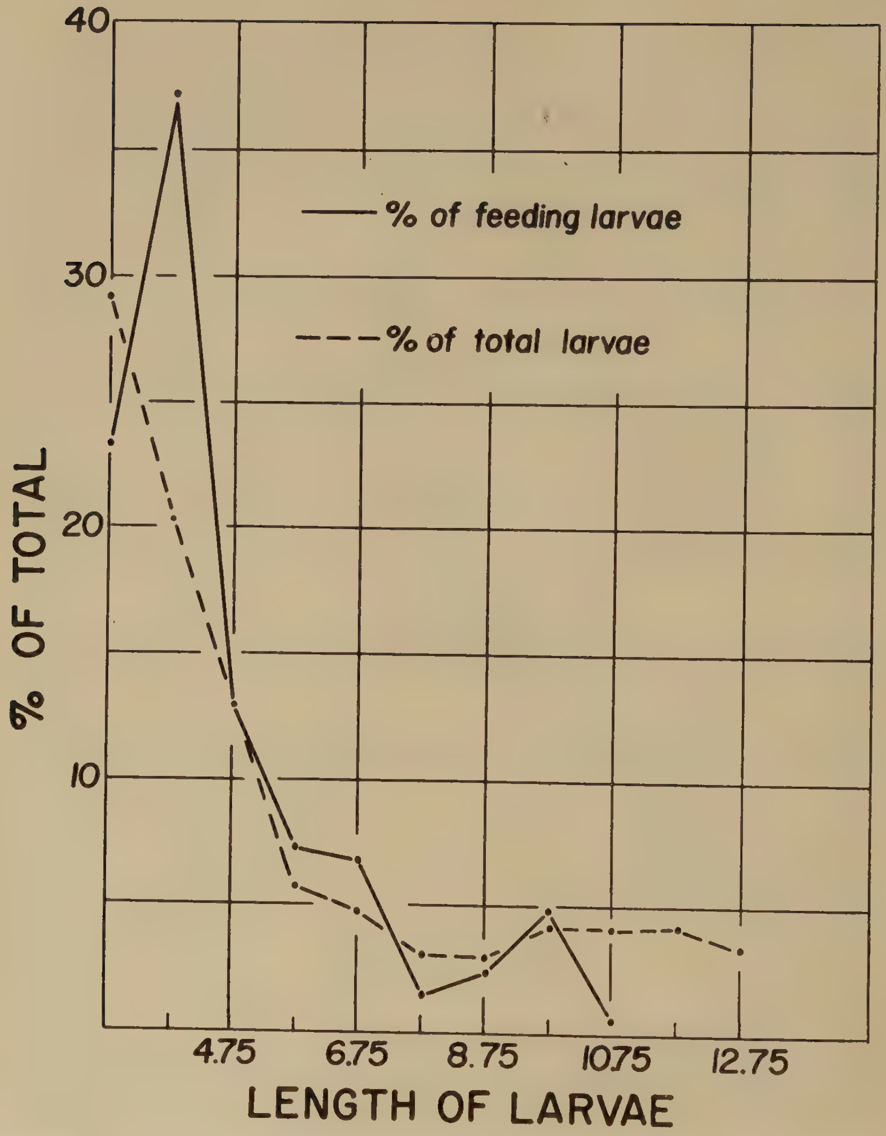

FIGURE 5. Comparison of the percentage of total larvae and the percentage of feeding larvae in various size groups, lengths in millimeters.

FIGURA 5. Comparación del porcentaje del total de larvas con el porcentaje de larvas alimentándose, distribuídas en varios grupos de tamaños; la longitud está indicada en milímetros.

TABLE 1. Size of food* ingested by anchovy and sardine larvae of various sizes.

TABLA 1. Tamaño del alimento* ingerido por las larvas de anchoas y sardinas de distintas dimensiones.

Length of anchovy larvae mm.	Food size anchovy (Present study) μ	Food size anchovy (from Arthur 1956) μ	Length of sardine larvae mm.	Food size sardine (from Arthur 1956) μ
Longitud de las larvas de anchoas mm.	Tamaño del alimento de la anchoa (Estudio presente) μ	Tamaño del alimento de la anchoa (Seg. Arthur 1956) μ	Longitud de las larvas de sardinas mm.	Tamaño del alimento de las sardinas (Seg. Arthur 1956) μ
3	24-186	20-100	4	20-80
5	50-200	20-140	7	70-130
10-12	25-250	240-270	10	80-200

*Measured along longest axis

*Medido a lo largo del eje más largo

TABLE 2. Number and per cent by number of food items of different sizes eaten by anchovy larvae.

TABLA 2. Número y porcentaje de los items de alimento de diferentes tamaños ingeridos por las larvas de anchoas.

Larval length mm.	No. of food items under 90μ	No. of food items over 90μ	% by No. less than 90μ	% by No. more than 90μ
Longitud de las larvas mm.	No. de los items de menos de 90μ	No. de los items de más de 90μ	% por No. menos de 90μ	% por No. más de 90μ
2.5-4.0	110	24	82	18
4.5-6.0	71	18	80	20
6.5-8.0	15	10	60	40
8.5-10.0	12	34	26	74
10.5-12.0	0	1	0	100
12.5-14.0	0	1	0	100
14.5-16.0	0	5	0	100
25	0	1	0	100
Total	208	94	69%	31%

TABLE 3. Composition of food found in guts of anchovy larvae, percentage by number.

TABLA 3. Composición del alimento encontrado en el intestino de las larvas de anchoas; porcentaje por número.

Food item	To 4.5 mm.		5-6.5 mm.		Longer than 7 mm.		Naturaleza del alimento
	1954 samples	Earlier samples[1]	1954 samples	Earlier samples	1954 samples	Earlier samples	
	Hasta 4.5 mm.		De 5-6.5 mm.		De más de 7 mm.		
	Muestras de 1954	Muestras anteriores[1]	Muestras de 1954	Muestras anteriores	Muestras de 1954	Muestras anteriores	
Copepod eggs	40.6	15.3	77.2	14.3	18.3	....	Huevos de copépodos
Copepod nauplii	5.1	42.9	5.4	67.0	12.7	90.0	Naupli de copépodos
Copepod adults	....	....	....	....	1.4	9.1	Copépodos adultos
Euphausiid eggs	....	....	3.3	....	4.2	....	Huevos de eufáusidos
Euphausiid nauplii	0.6	....	....	....	....	....	Naupli de eufásidos
Tintinnids	22.3	3.1	6.5	....	1.4	....	Tintinoides
Dinoflagellates	0.6	7.1	2.2	3.6	36.6	....	Dinoflagelados
Coccolithophores	....	4.1	....	....	....	....	Cocolitofóridos
Foraminifera	....	2.0	....	....	....	...	Foraminíferos
Clam larvae	....	2.0	....	....	2.8	....	Larvas de moluscos
Ciliates	....	....	....	7.1	....	....	Ciliados
Misc. plant mat.	3.4	21.4	....	7.1	5.6	....	Mat. vegetal misc.
Unident. eggs	8.0	....	1.1	....	8.5	....	Huevos no identificados
Misc. unident.	19.4	....	4.3	....	8.5	....	Mat. misc. no identificado

[1] After Arthur (1956).

[1] Según Arthur (1956).

TABLE 4. Comparison of numbers and feeding incidence for day and night caught larvae.

TABLA 4. Comparación del número e incidencia de larvas con alimento capturadas durante el día y la noche.

		Cruise 5401 Number Crucero 5401 Número	Cruise 5401 Feeding incidence Crucero 5401 Incidencia de la nutrición	Cruise 5404 Number Crucero 5404 Número	Cruise 5404 Feeding incidence Crucero 5404 Incidencia de la nutrición	Cruise 5407 Number Crucero 5407 Número	Cruise 5407 Feeding incidence Crucero 5407 Incidencia de la nutrición	Total all cruises Number Total todos los cruceros Número	Total all cruises Feeding incidence Total todos los cruceros Incidencia de la nutrición
Yolk sac—non-feeding larvae Larvas con saco vitelino—no alimentándose		906	0	612	0	161	0	1,679	0
Day-caught larvae Larvas capturadas de día—	Feeding Alimentándose	63	5.3	94	4.9	15	3.7	172	4.9
	Total number Número total	1,199		1,927		406		3,532	
Day-caught larvae (Including twilight) Larvas capturadas de día— (Incluído el crepúsculo)	Feeding Alimentándose	79	4.0	107	4.2	15	3.7	201	4.1
	Total number Número total	1,985		2,544		406		4,935	
Night-caught larvae Larvas capturadas de noche—	Feeding Alimentándose	24	0.5	15	0.3	0	0.0	39	0.4
	Total number Número total	5,068		4,603		417		10,088	
Total larvae Total de larvas	Feeding Alimentándose	87	1.4	109	1.7	15	1.8	211	1.5
	Total number Número total	6,267		6,530		823		13,620	

EL ALIMENTO DE LAS LARVAS DE LA ANCHOA NORTEÑA

ENGRAULIS MORDAX[1] [2]

por

Leo Berner, Jr.

El único trabajo publicado hasta ahora que trata sobre el alimento y nutrición de las larvas de la anchoa norteña, *Engraulis mordax* Girard, es el de Arthur (1956); pero su objeto principal fué la sardina del Pacífico, *Sardinops caerulea* (Girard), y el estudio dedicado a la anchoa solo puede considerarse como preliminar. La presente investigación es una continuación del estudio de Arthur sobre el alimento de las larvas de la anchoa norteña.

Las larvas que se utilizaron para el presente estudio (Tabla 3) fueron puestas a nuestra disposición por el Dr. E. H. Ahlstrom, del Grupo de Investigaciones sobre las Pesquerías del Pacífico Sur del Servicio de Pesca y Vida Silvestre de los Estados Unidos, y recolectadas durante el año 1954 frente a las costas de California y Baja California (Figuras 1-3) en el curso de las tomas de plancton que en forma rutinaria efectuó la entidad Investigaciones Cooperativas sobre Pesquerías Oceánicas de California. El autor desea expresar su agradecimiento a los Dres. Martin W. Johnson y Carl L. Hubbs por la lectura y crítica del manuscrito y por sus útiles sugerencias; así como a la Sra. Alice Theilacker por la ejecución de las figuras.

METODO

El método empleado para examinar las larvas fué similar al seguido por Arthur. Las larvas fueron extraídas del líquido en que habían estado preservadas—formol al 5%—y transferidas a glicerina al 95%, lo que tuvo varias ventajas. Las larvas se aclararon de modo que casi todas las partículas de alimento contenidas en el intestino pudieron localizarse sin necesidad de recurrir a la disección. Además, las larvas se hicieron más flexibles y menos expuestas a romperse durante la disección, ya que la mayor viscosidad de la glicerina amortiguó el movimiento, lo que facilitó la disección.

Después de aclararlas durante por lo menos 24 horas, las larvas fueron examinadas bajo un microscopio de pequeño aumento con el propósito de reconocer las partículas de alimento en el intestino. Como ocurre con las larvas de clupeidos, el intestino de la anchoa está suspendido debajo de la musculatura del cuerpo de modo que queda visible en toda su longitud, excepto en un corto trecho obscurecido por el hígado. Las larvas con alimento y las que estuvieron bajo la sospecha de contenerlo, fueron colocadas sobre un portaobjetos para ser examinadas con un microscopio de mayor aumento. Muchas partículas de alimento pudieron ser identificadas y medidas en el sitio; otras larvas se disecaron para estudiarlas más detenidamente.

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[1] Contribución del Instituto Scripps de Oceanografía, Nueva Serie.

[2] Este trabajo ha sido realizado mientras el autor trabajaba en el Ministerio del Interior, Servicio de Pesca y Vida Silvestre, Oficina de Pesquerías Comerciales, La Jolla, California, Estados Unidos.

NUTRICION

Soleim (1942) observó que el alimento ingerido por las larvas de arenque pasaba muy rápidamente a la parte posterior del intestino. Las partículas de alimento ingeridas por las anchoas, aparentemente pasan con rapidez por el esófago; en el curso de este estudio no se encontraron larvas con alimento en este órgano. Estudios preliminares sugerían que el alimento podría estar en las partes hinchadas que fueron observadas a lo largo del esófago de muchas larvas. La cuidadosa disección de cierto número de tales áreas hinchadas permitió ver que no contenían material alimenticio; se admite que representan gotitas de agua tomada durante las contorsiones de las larvas que entraban en el estado de coma. En un número algo menor de larvas se encontró que el intestino presentaba unas áreas largas y extendidas en forma de burbuja. En el curso del examen de estas áreas no se encontró ni resto de partículas de alimento.

Normalmente, el material contenido en el intestino pudo verse fácilmente a través del tejido circundante, pero algunas partículas bien digeridas sólo pudieron encontrarse al disecar áreas pequeños y extendidas del intestino. En algunas de las larvas de más de 12 mm. de longitud, la pared del intestino estuvo mal preservada cerca de las partículas de alimento aunque, por lo demás, dichas larvas estuvieron en excelentes condiciones. Aparentemente el formol había penetrado lentamente, de modo que las enzimas digestivas pudieron destruir el intestino desde el interior.

TAMAÑO DEL ALIMENTO

Arthur (1956) encontró que las larvas de anchoas ingerían alimento cuyo tamaño variaba entre límites mayores que el de las larvas de sardinas. Mis datos indican límites más amplios, aún para el tamaño del alimento de las larvas de anchoa capturadas en 1954, que los indicados por Arthur para las larvas examinadas por él (Tabla 1). Estas diferencias no pueden relacionarse con el efecto de las estaciones, pero queda la posibilidad de que el alimento disponible haya sido muy diferente en 1951-52.

A medida que las larvas crecen, se pone de manifiesto la tendencia hacia la ingestion de alimento de mayor tamaño (Tabla 2), pero esta tendencia es menos marcada que en la sardina. La Figura 4 presenta la distribución del tamaño de las partículas de alimento inferior a 300 μ en las larvas con una longitud entre 2.5 y 10 mm. Sólo hubo 4 items de alimento con un tamaño superior a 300 μ.

COMPOSICION DE LA DIETA

En las larvas de anchoas coleccionadas durante 1954, la composición efectiva del material alimenticio difiere en forma evidente de la encontrada por Arthur (Tabla 2). En efecto, en vez de llegar a ser menos eurífagas con el tamaño, las larvas de 1954 siguieron comiendo un material muy variado. Las larvas que medían más de 7 mm. fueron las que comían la mayor variedad de material. Crustáceos, principalmente copépodos en distintos estados de desarrollo, constituyeron el alimento de mayor tamaño de todos los grupos de larvas.

El alto porcentaje de dinoflagelados en las larvas con una longitud de más de 7 mm. resultó casi enteramente de los datos obtenidos en una estación. Una anchoa de 10 mm., de esta estación, contuvo 21 dinoflagelados y éste ha sido el mayor número de partículas de alimento encontradas en una larva.

INCIDENCIA DE LA NUTRICION

El porcentaje más alto de larvas con alimento se encontró entre las de menor tamaño; el grupo mayor tenía una longitud de 3.75 mm. (Figura 5). En los tamaños menores, de 2.5 y 3.0 mm., la proporción de las larvas con alimento disminuye bruscamente debido al predominio de las larvas poseedoras de saco vitelino que no se alimentan. Ninguna de las larvas con ojos sin pigmentar contenía alimento. La pérdida del vitelio y el desarrollo de pigmento en los ojos suelen ocurrir simultáneamente. Una merma evidente existe también en el porcentaje de larvas con alimento en los grupos de mayor tamaño, representadas en las muestras examinadas. En larvas con una longitud mayor de 10 mm., raras veces se encuentra alimento. Entre los 4.5 y los 9.5 mm., la merma en el porcentaje de larvas con alimento es paralela a la merma en el porcentaje del total de larvas de cada grupo de tamaño. El porcentaje de las larvas con alimento, que miden más de 9.5 mm., cae rápidamente a un nivel muy bajo.

Lebour (1918, 1919, 1920 y 1921), quien estudió el alimento de muchos peces en el estado larval, afirmó (1921) " . . . fueron examinados algunos millares de clupeidos jóvenes, encontrándose que el porcentaje más elevado de postlarvas era el de las vacías". Otras investigaciones sobre la nutrición de las larvas de clupeidos mostraron la misma baja incidencia en la alimentación de las larvas. La incidencia general de las larvas con alimento, indicada por los datos del crucero de 1954, ha sido muy baja; en un total de 13,620 larvas que podían nutrirse potencialmente, sólo se encontraron 211 larvas conteniendo alimento. En este ejemplo no están incluídas las larvas con saco vitelino.

La incidencia de las larvas con alimento, de cualquier crucero, no difiere en forma apreciable de la incidencia general de 1.5%. Pero, al comparar la incidencia de la nutrición nocturna con la diurna, se observa que la incidencia diurna supera a la nocturna por lo menos 10 veces (Tabla 4). Al definir el término "diurno" como abarcando el período entre la salida y la puesta del sol, resulta que el 81.5% de las larvas con alimento fué capturado en los arrastres de plancton hechos durante el día; pero si se considera 45 minutos para el crepúsculo, resulta que el 95.3% de las larvas con alimento se capturó en el curso de las horas con luz de día. Sólo el 32.7% del total de las postlarvas con saco vitelino fué tomado en capturas hechas en horas con luz de día y luz crepuscular, por lo cual el 95.3% de las larvas con alimento se encuentra en sólo el 32.7% de las larvas. Esto indica que las larvas de anchoas dependen de su sentido visual durante la nutrición.

Al examinar las cartas (Figura 1-3) que indican los lugares de captura de las larvas de anchoas durante los tres cruceros considerados, puede observarse que las estaciones en que se obtuvieron las larvas con alimento no están distribuídas por toda la región, sino que tienden a presentarse en ciertas áreas. Estas se encuentran al sur de Punta Concepción y Punta Eugenia, respectivamente, y son las áreas de concentración de los organismos con que se alimentan las larvas de peces (Arthur, 1956).

CONDICION FISICA DE LAS LARVAS

En el curso de esta investigación nos sorprendió el gran número de larvas preservadas en malas condiciones que encontramos en las muestras. Muchas habían perdido sus ojos y estaban bastante flácidas; en algunas el hígado estaba consumido casi por completo. Resultó imposible determinar en forma positiva si estas malas condiciones se debían a daños sufridos por las larvas al ser capturadas vivas, a una mala preservación y tratamiento inadecuado después de la captura, o al hecho de que las larvas estuvieran ya muertas o al morir en el momento en que se capturaban. También otros investigadores han encontrado en sus muestras larvas presumiblemente muertas antes de la captura. Soleim (1942) informó en su trabajo sobre el arenque, *Clupea harengus,* que las muestras contenían larvas que ya estaban muertas cuando fueron tomadas en los rastreos planctónicos. Marr (1956: 167-168) se expresó en el sentido de que eso puede ser la consecuencia de algún artefacto introducido durante el lavado descuidado de la red planctónica; cita a su vez, sin embargo, otros ejemplos de larvas que estaban muertas al ser capturadas. Arthur (1956) informó sobre un número considerable de larvas de sardinas en mala condición; asumiendo que pudieron haber estado muertas, en un alto porcentaje, en el momento de la captura. Hizo una tabulación (1956: 105) de las diferencias morfológicas entre las larvas bien y mal preservadas, basado en el examen detenido de un gran número de larvas. Parece probable que un número significante de larvas capturadas mediante las tomas rutinarias de plancton y examinadas en este trabajo, estuvieron ya sea muertas o bien muriéndose en el momento de la captura. El aspecto del hígado puede considerarse como uno de los mejores indicadores de la condición de las larvas en este momento; en las larvas mal preservadas, un hígado grande e intacto sugiere que se trata de una larva que ha sido dañada durante la captura o la preservación, mientras que un hígado casi consumido sugiere una larva que estaba muriéndose al ser capturada o que se encontraba entonces en estado de inanición.

Las larvas de anchoas con una longitud mayor de 15 mm. por lo general estaban bien preservadas, a pesar de la incidencia extremadamente baja de su nutrición. La mayoría de estas larvas de mayor tamaño se capturó durante la noche cuando, de acuerdo con los datos que poseemos, menos se espera que contengan alimento. Una explicación comprensible de este fenómeno es la de que las larvas mayores son capaces de eludir la red mientras hay luz solar y se nutren y que sólo se capturan de noche cuando no se alimentan. La reducida colección de larvas grandes de sardinas durante el día fué examinada por Ahlstrom (1954: 129-130) y sus datos tienen validez también para las anchoas.

DISCUSION

La baja incidencia de alimentación encontrada en las larvas de clupeidos llevó a especulaciones considerables. Al tratar la razón de la falta de alimento en clupeidos jóvenes, Lebour (1921: 458) sugirió como causa probable de la falta de alimento en los estados transparentes, la de que el alimento se digiere rápidamente porque, de otra manera, su presencia en el intestino haría a las larvas muy visibles; según esta sugerencia, el alimento se ingiere sólo a grandes intervalos y pasa rápidamente por el intestino. Resultaría, en estas circunstancias, que sólo casualmente podrían capturarse peces con alimento. Arthur (1956) admitió dos otras posibilidades, que son las siguientes: la primera, sugerida por el Dr. Carl L. Hubbs, es la de que el cuerpo acuoso y gelatinoso del tipo leptocefálido de las larvas de clupeidos requiere menos alimentación por unidad de volumen que las larvas con un cuerpo más sustancioso; la segunda, que él describió ampliamente, aunque sólo la aplicó a la sardinas, es la de que las larvas sanas pueden escapar a la red, de modo que las capturadas representan un porcentaje desproporcional de larvas enfermas y moribundas. Mi propia observación de que entre las larvas examinadas parecía haber un número desproporcionado de individuos "muertos", muy mal preservados, entra dentro de esta hipótesis alternativa. Probablemente todos estos factores intervienen hasta cierto punto, pero no puede hacerse estimación alguna sobre su importancia relativa.

Morris (1955) sugirió que los peces marinos pueden obtener parte de su alimento de la materia orgánica "disuelta" y esbozó un mecanismo para su uso; para sostener su punto de vista, escribió (página 258): "Entre gran número de larvas mantenidas en el laboratorio no he visto indicación alguna de que la digestión se desarrolle a un ritmo muy rápido, ni tampoco pareció ser muy completa". Lamentablemente, no dijo a qué larvas hacía referencia, ni tampoco definió el concepto "rápido". Más tarde (1956), dió una lista de las larvas que había mantenido y por cuánto tiempo consiguió tenerlas, sin agregar nada, sin embargo, sobre el ritmo de la digestión o su eficiencia. En una comunicación personal dirigida a Arthur, dejó establecido que las larvas de anchoas de unos 30 a 40 mm., con el intestino vacío, eliminaban heces a una hora o a una hora y cuarto después de haberse colocado alimento en el tanque.

Volviendo a nuestras muestras, poco es lo que puede decirse sobre la velocidad de la digestión. Sin embargo, en dos muestras tomadas dentro de los 45 minutos después de la puesta del sol, todas las partículas alimenticias presentes se vieron en las partes posteriores del intestino. La digestión de la mayor parte del material encontrado en los intestinos de la anchoa se había hecho casi totalmente. Los naupli de copépodos sólo pudieron identificarse mediante su exoesqueleto quitonoso, que parecía un dibujo lineal, ya que todo el material interior había sido digerido.

Indiferentemente de la explicación que se dió, todos los estudios del contenido estomacal de los clupeidos muestran una baja incidencia de la nutrición. El examen definitivo de cualesquiera de las hipótesis expresadas, o de una combinación de ellas, para explicar esta aparente ausencia de alimento, no podrá basarse en el estudio de larvas preservadas, sino que deberá hacerse sobre ejemplares vivientes en forma experimental y bajo condiciones similares a las existentes en la naturaleza.

LITERATURE CITED—BIBLIOGRAFIA CITADA

Ahlstrom, E. H.

1954 Distribution and abundance of egg and larval populations of the Pacific Sardine.
U. S. Dept. Int., Fish and Wildlife Serv., Fish. Bull. 93, pp. 83-140.

Arthur, David K.

1956 The particulate food and food resources of the larvae of three pelagic fishes, especially the Pacific sardine, *Sardinops caerulea* (Girard).
Unpublished doctoral dissertation, on file in the library of Scripps Institution of Oceanography, University of California, La Jolla, 231 pp.

Lebour, M. V.

1918 The food of post-larval fish.
Jour. Mar. Biol. Assoc. U. K., Vol. 11, pp. 433-469.

1919 The food of post-larval fish. No. II.
Ibid., Vol. 12, pp. 22-47.

1920 The food of young fish. No. III.
Ibid., Vol. 12, pp. 261-324.

1921 The food of young clupeoids.
Ibid., Vol. 12, pp. 458-465.

Marr, J. C.

1956 The "critical" period in the early life history of marine fishes.
Jour. Cons. Internat. Expl. Mer, Vol. 21, No. 2, pp. 160-170.

Morris, Robert W.

1955 Some considerations regarding the nutrition of fish larvae.
Jour. Cons. Internat. Expl. Mer, Vol. 20, No. 2, pp. 255-265.

1956 Some aspects of the problem of rearing marine fishes.
Bull. Inst. Oceanographique, Vol. 53, No. 1082, pp. 1-61.

Soleim, P. A.

1942 Årsaker til rike og fattige årganger av sild.
Fisjeriderektoratets Skrifter, Ser. Havundersokelser, Vol. 7, No. 2, 39 pp. (English summary, 2 pp.).

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VOLCANISM IN EASTERN PACIFIC OCEAN BASIN: 1945-1955

Sobretiro de la

Sección I — Vulcanología del Cenozoico
(Primer Tomo)

págs. 19-31, 1 tabla, 4 figs.

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1957

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VOLCANISM IN EASTERN PACIFIC OCEAN BASIN: 1945-1955 *

A. F. Richards **

ABSTRACT

During the last decade active volcanism, exclusive of fumarolic activity, in the eastern Pacific basin appears to have been confined to the Islas Revillagigedo of Mexico and the Islas Galápagos of Ecuador.

In the Revillagigedo a new volcano, named Bárcena was born on Isla San Benedicto August 1, 1952. A cinder cone 390 m high formed by August 12, trachyte was extruded into the crater in November and a delta of lava developed between December and February 1953. Large crater solfataras became inactive in 1954.

In the Galápagos volcanic activity was limited to Isla Isabela (Albemarle Island). Flank and/or crater eruptions occurred on Volcán Wolf. Volcán Alcedo, Sierra Negra and Cerro Azul between 1945 and 1955. Early in 1954 the shore of Bahía Urvina on the west flank of Volcán Alcedo was uplifted, apparently by the ascent of magma which was erupted in November.

INTRODUCTION AND ACKNOWLEDGEMENTS

In the eastern Pacific Ocean basin there are four principal areas of active volcanism, including submarine and fumarolic activity. These are: 1) Islas Revillagigedo of México; 2) Islas Galápagos of Ecuador; 3) Isla San Felix of Chile; and 4) Islas Juan Fernández of Chile. During the past decade volcanic eruptions, exclusive of fumarolic activity, have occurred on Isla San Benedicto in the Islas Revillagigedo and on Isla Isabela in the Islas Galápagos. Because no reports have been received of eruptions in the Chilean islands it is presumed that they were inactive during this period.

A new (volcanic) island, Carabobo, off northwest Colombia in an unknown location, appeared in 1945 and later disappeared (Hantke, 1951, p. 174). Carabobo was located near the Gulf of Darien in the Atlantic Ocean (Anonimous, 1945a, 1945b).

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** *Scripps Institution of Oceanography, La Jolla, Calif.*

No submarine eruptions in the eastern Pacific Ocean are known difinitely to have occurred. However, a submarine eruption in July, 1953, of a new volcano in Bahía San Cristóbal off the west coast of Baja California (27° 25′ N lat., 114° 35′ W long.), has recently been reported (González Reyna, 1956, p. 25). This "eruption" was investigated on July 20, 1953, by Captain Noel Ferris of the Scripps Institution R/V *Horizon* at the radiotelephone request of Mr. James Snodgrass and the writer, who, a day later, also searched the area from a U. S. Coast Guard airplane. No evidence of volcanic activity or dead fish was seen from ship or plane. Radio sonobuoys (see Snodgrass and Richards, 1956) were dropped in the vicinity of the reported eruption in order to listen for underwater sounds of volcanic origin. None were heard or tape recorded. The reported bubbles undoubtedly were caused by rotting kelp on the sea floor or other biological rather than volcanological activity.

The development of Volcán Bárcena on Isla San Benedicto was studied by the author by air, sea and land between 1952 and 1956. He has not visited the Galápagos; however, reports of volcanic activity have been obtained from tuna fishermen, yachtsmen and the Walt Disney Productions expedition of 1954.

The writer is particulary grateful to the many men of the California tuna clipper fleet who have contributed information on current volcanism in the eastern Pacific. Captain George Zeluff of the M/V *Paramount* is thanked for having investigated activity and verified reports in both archipelagos. Mr. Robert S. Robbins of the M/V *Normandie* furnished information on the 1954 eruption of Volcán Alcedo. Photographs and information on the Bahía Urvina uplift were kindly given the writer by Walt Disney Productions, Inc., through the courtesy of their True Life Adventures department, and by Captain Peggy Poor of the yacht *Windjammer*. Additional information on the uplift was obtained by interview of Mr. Jack C. Couffer of Canyon Films, who generously allowed the use of his unpublished notes. Prof. Chas. H. Behre, Jr. assisted with the names of Isla Isabela volcanoes.

BIRTH AND DEVELOPMENT OF VOLCAN BARCENA, ISLA SAN BENEDICTO

In 1952 a new volcano was born on the isolated and uninhabited oceanic island of Isla San Benedicto. This was the first historic pumice eruption in the eastern Pacific Ocean (Williams, 1952). San Benedicto, 447 m long, is the northeastern island in the Revillagigedo archipelago. It is located 685 km west of Manzanillo, Colima, 408 km south of Cabo San Lucas, Baja California and 1,752 km southeast of Los Angeles, California (Fig. 1).

The island is composed of olivine basalt, basalt, basaltic andesite, trachyan-

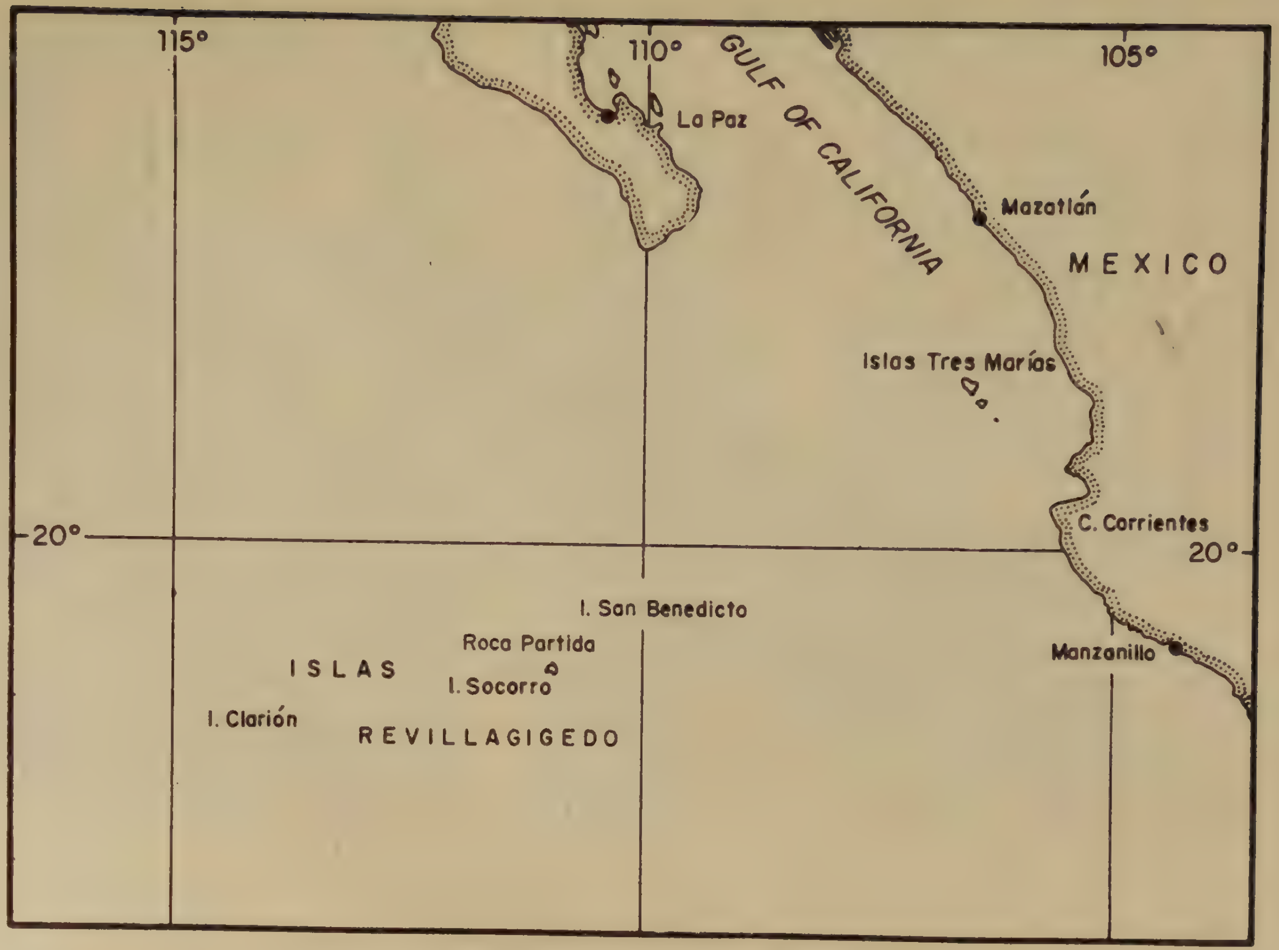

115°
110°
105°
20°
20°
La Paz
GULF OF CALIFORNIA
Mazatlán
MEXICO
Islas Tres Marías
C. Corrientes
Manzanillo
I. San Benedicto
Roca Partida
I. Socorro
ISLAS
REVILLAGIGEDO
I. Clarión

FIG. 1
Location map of the Islas Revillagigedo.

desite(?), trachyte, quartz trachyte and pyroclastic material. Trachyte is most abundant.

In the early 19th century Humboldt (1811, p. 221) suggested that an east-west chasm at great depth in the interior of the earth extended from the Gulf of México to the South Sea; it included Volcán Jorullo and perhaps extended to the Islas Revillagigedo at the same latitude. More recently Menard (1955, pp. 1167-1169) proposed that the submergent features of the Clarión fracture zone, which extends over 5,500 km west of Isla Clarión, are related to the Islas Revillagigedo and the trans-México volcanic zone. Although Clarión may be genetically related to the Clarión fracture zone detailed bathymetric surveys by the writer show that San Benedicto and Socorro have a north-south alignment and perhaps are related to a little explored range of seamounts which trend south of Socorro.

Activity of Volcán Bárcena between August 1952 and November 1953 has been described in a preliminary paper by Richards and Dietz (1956). A final report is in preparation by the writer.

The name Boquerón, meaning Big Mouth, was originally suggested for the new volcano on San Benedicto by Prof. Howel Williams and was proposed by Dietz (1953, p. 26). In 1953 the late Ing. Teodoro Flores, Director of the Instituto de Geología in México, suggested the name Bárcena in honor of the distinguished Mexican geologist, Mariano Bárcena. This name has been adopted.

DEVELOPMENT OF THE CONE

Volcán Bárcena was born on the northeast flank of the old, eroded, pyroclastic cone of Montículo Cinerítico on the southern end of San Benedicto (Fig. 2) at 0745 on the morning of August 1, 1952. The initial eruption was witnessed by men of the tuna clipper M/V *Challenger* who took photographs of the violent vulcanian-type activity.

In addition to a rising eruption column of ash and gas a dark cloud spread out laterally. It was similar to the base surge of an atomic explosion. Within twenty minutes after the begining of the eruption Isla San Benedicto was nearly obscured from view as the *Challenger* steamed away from the island at full speed.

On August 12 San Benedicto was visited by the M/V *Intrepid*. Mr. Chester Blasko flew to San Benedicto from Socorro, a distance of about 67 km, in the fish-spotting seaplane of the *Intrepid*. Motion pictures taken on the flight show that Bárcena was still in violent vulcanian-type eruption. The film shows that small glowing avalanches (non-incandescent when seen in daylight) periodically poured over the crater rim and rushed down the cone toward the

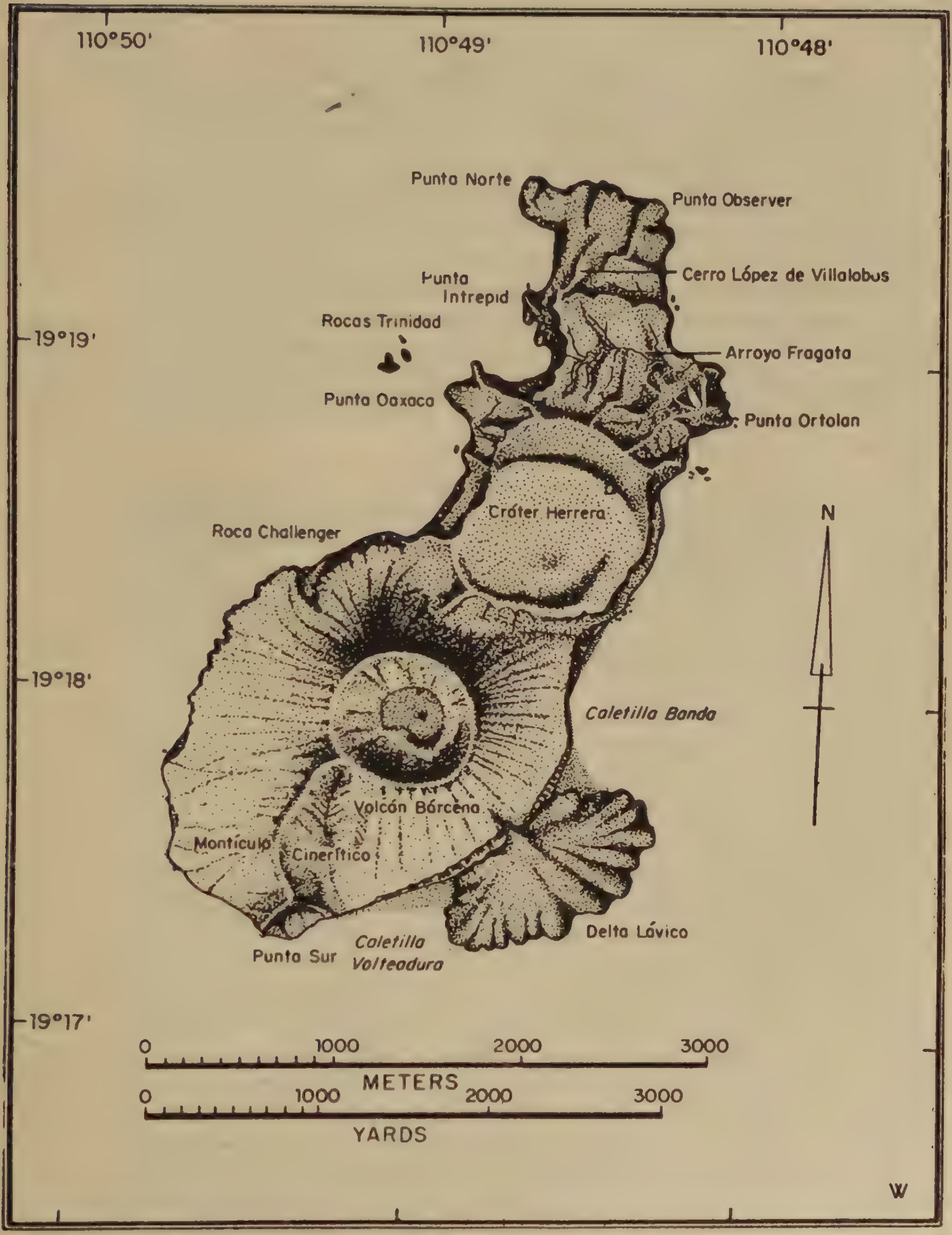

110°50'
110°49'
110°48'
Punta Norte
Punta Observer
Cerro López de Villalobos
Punta Intrepid
Rocas Trinidad
Arroyo Fragata
Punta Oaxaca
Punta Ortolan
Cráter Herrera
N
Roca Challenger
19°19'
19°18'
19°17'
Caletilla Banda
Volcán Bárcena
Montículo
Cinerítico
Delta Lávico
Punta Sur
Caletilla Volteadura
0
1000
2000
3000
METERS
0
1000
2000
3000
YARDS
W

FIG. 2
Map of Isla San Benedicto, from aerial photographs.

sea. The ascent of the erupted material was measured by vertical sextant angle from the *Intrepid* at Socorro to be greater than 3 km. The films show that by this time, twelve days after birth, a pyroclastic cone formed from near sea level to an altitude of about 390 m.

The dust and ash of the cone is trachyte, slightly higher in silica, soda and potash than the later crater and delta flows. Pumice from the cone contains phenocrysts of sanidine, albite and aegerine-augite in a matrix of glass.

On September 20 Bárcena was seen and photographed from the air on a U. S. Air Force flight by Dr. Dietz, Prof. Williams and Mr. Ernest Boldrick. Visible activity had temporarily come to an end, except for the escape of steam and a little hydrogen sulfide. Two small domes of blocky lava had apparently plugged the conduit of the crater, which was estimated to be 210 m deep and 610 m wide at the rim (cf. Fig. 2).

EXTRUSION OF CRATER LAVA

In November Bárcena became active again and blocky trachyte with occasional olivine basalt xenoliths was extruded into the crater, half-filling it, between about November 12 and early December. Steam together with a little ash continued to be emitted during this period. The volcano was observed from sea by tuna fishermen and from a U. S. Navy plane by Dr. Douglas Inman, Mr. James Snodgrass and the writer.

FORMATION OF THE DELTA LÁVICO

On December 8 a landslide occurred on the eastern sea cliff of Bárcena, according to reports of men of the M/V *Challenger* and M/V *Star of the Sea*. Lava issued from the site of the landslide and flowed down the cliff and across a small beach, reaching the sea on the morning of the 9th. That afternoon Mr. Lewis W. Walker and the writer reached San Benedicto on the yacht *Observer* for a four-day visit. By the 11th a scoriaceous black lava flow had formed a delta (Delta Lávico) of augite-oligoclase trachyte about 370 m wide, approximately 300 m out to sea and 21 m above sea level.

Between the 9th and 11th Bárcena periodically emitted steam and ash from a vent in the center of the dome in the crater. At dawn on the 12th a single, small, black-appearing, non-incandescent glowing avalanche overflowed the crater rim, swept down the flank, across the Delta Lávico and out to sea. Following the expulsion of the cloud Bárcena became continuously active. The volcano was last seen on December 13 by tuna fishermen who radioed that the activity appeared stronger than that of the 12th.

The last flow of lava in the Delta Lávico and weak steam and ash eruptions from the crater was witnessed at the end of February 1953 by men of the M/V *Columbus*.

Solfataric phase

San Benedicto was visited for six days in March 1953 by an expedition from the Scripps Intitution of Oceanography. Except for solfataric activity in the crater, above the Delta Lávico vent and on the delta, all activity had stopped. Between 1953 and 1956 a number of U. S. Navy photographic and observation flights were made to the island at the request of the Scripps Institution. The Delta Lávico was determined by photogrammetry to extend 640 m out to sea and have a maximum width of 1,180 m. Its height above sea level was about 30 m and probably one third of its volume was below sea level.

Crater solfataric activity of primary magmatic origin stopped between November 1953 and August 1954. Secondary solfataric activity, from cooling lava flows, has not yet ceased.

ISLAS GALAPAGOS

In historic time volcanic eruptions or fumarole activity have been reported on the islands of Fernandina, Isabela, Marchena, Pinta, San Salvador and Santa María (Fig. 3). The most active volcanoes occur on Isla Fernandina (Narborough Island) and Isla Isabela (Albemarle Island), at the western end of the archipelago.

On Isla Isabela all five of the mejor volcanoes (Fig. 3) have had flank or crater eruptions, or both, in historic time. During the last decade four of the five were active (Table 1). The reconnaissance geology of Isabela has recently been described by Banfield, Behre and St. Clair (1956). A more complete report on the emergence of the shore of Bahía Urvina is in preparation by the writer.

TABLE I

LIST OF VOLCANIC ACTIVITY ON ISLA ISABELA 1945-1955

Volcano	Date	Location of vent	Material erupted
Wolf	1948	East flank	Lava, little ash
Alcedo	1954	Crater and north flank	Lava, ash
Sierra Negra	1948	Not known	Ash (lava?)
	1953	North-northwest flank	Lava
Cerro Azul	1949?	Crater and flank(?)	Lava
	1951	Not known	Lava

No samples of lava or ash appear to have been collected from eruptions in the last ten years and little is known about the lavas of Isabela. The few described specimens are basaltic lavas and tuffs (see Richardson, 1933, pp. 51-53, 55-61 and Banfield, Behre and St. Clair, 1956, p. 227). Bathymetric evidence for connections between the Islas Galápagos and the continent has described recently by Shumway (1954).

VOLCÁN WOLF

The flank eruption of Volcán Wolf in 1948 has been described by Captain Joseph Madruga of the M/V *Paramount* (Richards, 1954, p. 3) and mentioned by Hantke (1953, pp. 161-162). A light-colored eruption of steam and perhaps a little ash apparently began on January 24 and was witnessed from the *Paramount* in Bahía Banks 20 km southwest of the volcano. That night incandescent bombs were ejected from the vent. On the 25th Captain Madruga was flown to the site of the outburst in the Piper Cub fish-spotting seaplane of the *Paramount*. A cone estimated to be 30 m high was observed at an approximate altitude of 1,218 m on the southeastern side of Wolf, which has a maximum altitude of about 1,700 m. Lava from the cherry-red crater of the cone appeared to flow over the rim, down the cone and towards the eastern coast. Several days later steam was noticed rising from the shore and it is probable that the lava reached the sea after flowing a distance of about 6,4 km. Lava flowing a short distance from the cone was seen on the 25th.

At the end of January, or early in February, a red glow in the from the sky from the eruption could be seen from the *Paramount* 156 km to the north. The date when the activity stopped is not known.

VOLCÁN ALCEDO

Uplift of the shore of Bahía Urvina.—The north and east floor of Bahía Urvina was elevated above sea level probably in early 1954. The emergence was discovered in March by the yacht *Highlander*, which was under charter to Walt Disney Productions, Inc. A brief report of the uplift was sent to the U. S. Hydrographic Office, which published the first notice of the phenomena in July 1954. A second account, based on a July visit by the yacht *Tropic Bird* (also under charter to Disney) was described in a published letter by Commodores Pat and Leo Miner (Seven Seas Cruising Association, 1954). Additional information on the uplift has been obtained from: unpublished notes and an interview with Mr. Jack Couffer, who visited the bay on both ships; photographs owned by Walt Disney Productions, which were taken by Mr. Couffer; an interview and photographs taken by Captain Peggy Poor of the yacht *Windjammer*, who visited Bahía Urvina in June; and an interview with Captain Zeluff of the M/V *Paramount*, who visited the bay on several

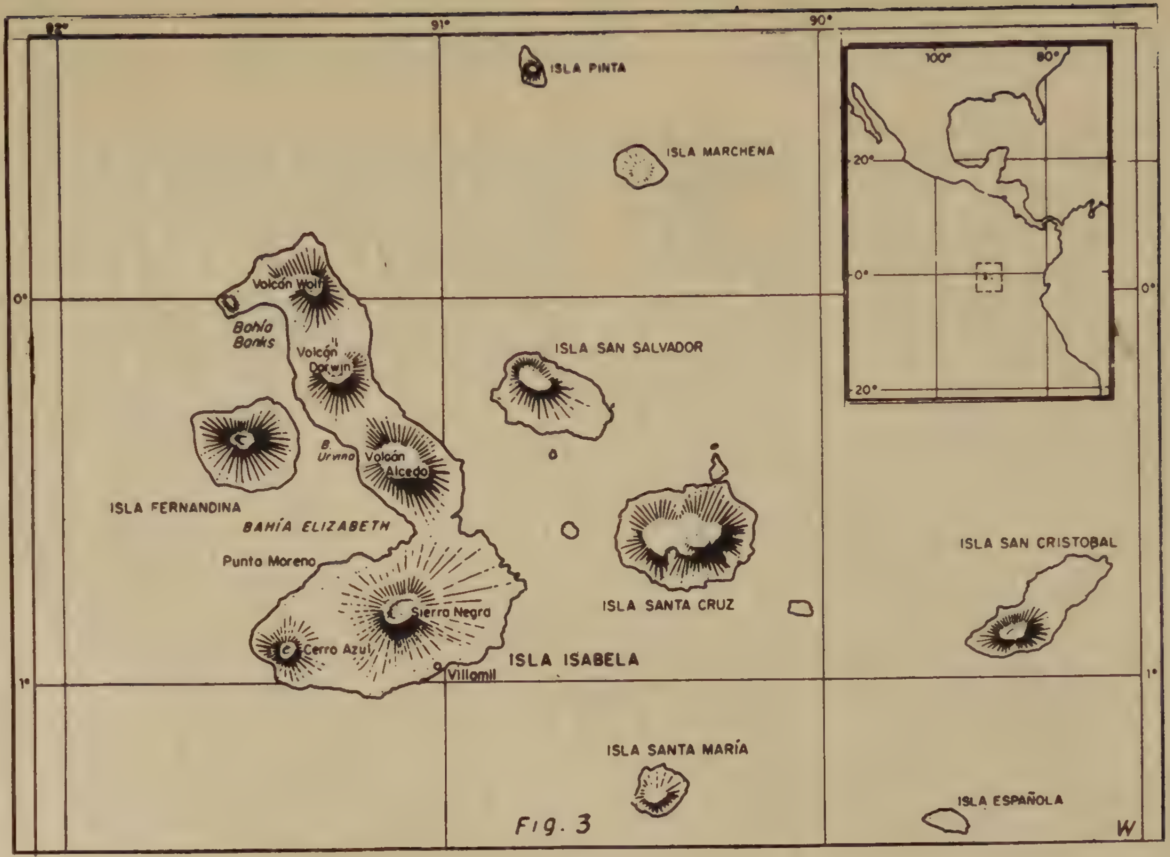

92°
91°
90°
0°
1°
ISLA PINTA
ISLA MARCHENA
Volcán Wolf
Bahía Banks
Volcán Darwin
ISLA SAN SALVADOR
ISLA FERNANDINA
B. Urvina
Volcán Alcedo
BAHÍA ELIZABETH
Punto Moreno
Sierra Negra
Cerro Azul
Villamil
ISLA ISABELA
ISLA SANTA CRUZ
ISLA SAN CRISTOBAL
ISLA SANTA MARÍA
ISLA ESPAÑOLA
Fig. 3
W
100°
80°
20°
0°
20°

Fig. 3

Location map of the Islas Galápagos, from Río Mira-Islas Galápagos map by the American Geographical Society of New York. Isla Darwin and Isla Wolf, north of map, are not shown.

occasions. A popular account of the emergence has been written by Couffer (1956).

The new configuration of Bahía Urvina (Fig. 4) has been compared to stereo-vertical photographs of the bay taken by the U. S. Air Force in 1946. The emergence was confined to reefs in the northern part of the bay and along the eastern shore for a distance of about 6 km. The seaward margin of the uplift extends a maximum of about 1.2 km from the old shore just west of the head of the bay. Vertical elevation averages 4.6 m and is comparatively flat, with practically no tilt to the lava and coral reefs. For the following reasons it is probable that the uplift was rapid and occurred shortly before the March visit by the *Highlander:* 1) The reef was covered with skeletal remains of crabs, starfish, sea urchins and fish. Decaying flesh still remained on lobsters, turtles, eels, fish and marine worms when partly protected from direct sunlight, 2) Shells collected by Mr. Couffer were identified by Mr. E. P. Chace, Curator of Conchology in the San Diego Natural History Museum, who said that their appearance indicated that the animals must have died in their shells quickly (personal communication), 3) Photographs taken by Mr. Couffer in March show that spines were still attached to sea urchins clustered at the base of the coral or algal incrusted lava boulders.

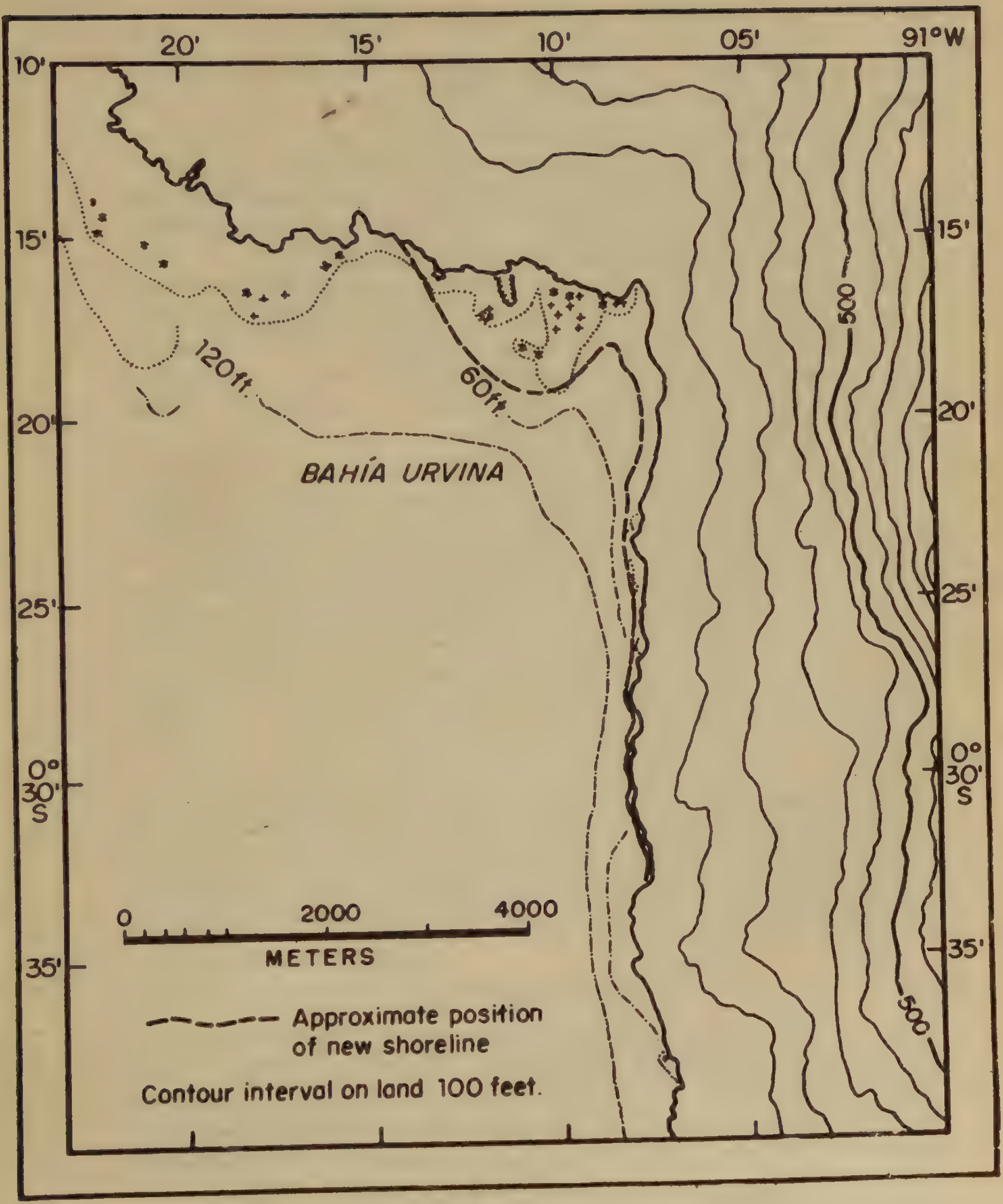
The uplift is believed to have been caused by tumescense of rising lava in Volcán Alcedo. According to visitors to the bay few signs of earthquakes were seen.

Eruption of Alcedo.—On November 9, 1954, a radio message that Volcán Alcedo had commenced to erupt was sent to the writer by Captain Marques of the M/V *Normandie.* Mr. Robert S. Robbins, navigator and radio operator of the *Normandie,* later told him that the outbreak occurred on the north-northeast flank of Alcedo from an altitude estimated to be 610 m. It was first witnessed from about 70 km northeast of the volcano. Small pencil-like spurts of gray steam and ash ascended from the area of the vent, which was marked by a red glow; they did not rise as high as the 1,177 m altitude of the crater rim. Shimmering heat waves appeared above the main crater by day and at night there was a continuous red glow. According to Mr. Robbins "the whole rim appeared to be on fire."

On the 10th, when the *Normandie* was on the west side of Isla Isabela, lava was seen flowing to the northwest from a high altitude on the flank of the volcano. The *Normandie* left Isabela on the 10th, and no information has been obtained of subsequent activity.

SIERRA NEGRA

According to Banfield, Behre and St. Clair (1956, p. 226) an eruption occurred on Sierra Negra (Volcán Grande or Volcán Sto. Tomás) in 1948.



20'
15'
10'
05'
91°W
10'
15'
20'
25'
0° 30' S
35'
500
120ft.
60ft.
BAHÍA URVINA
0
2000
4000
METERS
Approximate position of new shoreline
Contour interval on land 100 feet.

FIG. 4

Map of Bahía Urvina, Isla Isabela, from U. S. Hydrographic Office Chart No. 5929.

"Fine material" (presumedly ash) was noticed in the settlement of Santo Tomás on the southern flank of the volcano, which has an altitude of about 1,490 m. No additional details were given.

A flank eruption occurred on the north-northwest side of Sierra Negra on August 27, 1953. The eruption was reported by radio from several tuna clippers to the U. S. Hydrographic Office (1953) and the Scripps Institution. The following is a summary of the activity (Richards, 1954).

The beginning of the eruption was witnessed from the *Paramount* when steaming between Isla Fernandina and Isla Isabela. Captain Zeluff reported that the site of the fissure was at an approximate altitude of 1,130 m; the vent was about 3.7 km long and probably trended northeast. Apparently it was located near Volcán Chico, a parasitic cone on northern Sierra Negra (Banfield, Behre and St. Clair, 1956, p. 226).

On August 27 a large, light-colored eruption of gas rose from the fissure to a height in excess of 9 km and lava was seen flowing down the flank towards the sea. One flow traveled due north and apparently reached Bahía Elizabeth, a distance of about 9.3 km. The flow traveling northwest from the fissure branched several times and tongues flowed to either side of Punta Moreno, which is located about 18.5 km from the fissure. One of the north branches may have reached the sea; the western ones did not. Lava fountains, or showers of incandescent cinder, ascended an estimated 120 m above the vent at intervals of seven to nine minutes. The northern extremity of the fissure appeared to be most active.

Mr. Ray Maceris of the M/V *Equator* reported the eruption was seen on October 7 from Isla Baltra, which is 100 km northeast of Sierra Negra. The violent phase of the eruption stopped between October 7 and the end of January 1954 when Captain Zeluff observed only fumarolic activity. In the middle of February 1955 the *Paramount* again visited Isla Isabela. Steam was seen rising to a height of about 15 m above the red and white solfatara deposits at the fissure.

CERRO AZUL

Cerro Azul was in eruption in 1949(?) and 1951 (Banfield, Behre and St. Clair, 1956, pp. 225-226). Presumedly in 1949 lava from a flank eruption of the volcano, which has an altitude of about 1,660 m, blocked the trail from the village of Villamil and may have coincided with a small eruption in the crater of Cerro Azul (Chas. H. Behre, Jr., personal communication). No information about the 1951 eruption is available.

BIBLIOGRAPHY

ANONIMOUS. 1945a. New island rises off Colombia. *The New York Times*, v. XCIV, May 21, p. 9.

— 1945b. Island off Colombia disappears. *The New York Times*, v. XCV, Sept. 20, p. 4

BANFIELD, A. F., H. BEHRE, JR. and D. ST. CLAIR. 1956. Geology of Isabela (Albemarle) Island, Archipiélago de Colón (Galápagos). *Bull. Geol. Soc. America*, 67:215-234.

COUFFER, J. C. 1956. The disappearance of Urvina Bay. *Natural History*, v. , p.

DIETZ, R. S. (ed. by D. G. KELLEY). 1953. Boquerón. *Pacific Discovery*, VI:24-27.

GONZÁLEZ REYNA, J. 1956. A new volcano. *Proc. Eighth Pacific Sci. Congr., Phillipines*, II:25.

HANTKE, G. 1951. Übersicht über die vulkanische Tätigkeit 1941-1947. *Bull. Volcanologique*, Sér. II, XI:161-208.

— 1953. Übersicht über die vulkanische Tätigkeit 1948-1950. *Bull. Volcanologique*, Sér. II, XIV:151-184.

HUMBOLDT, A. von. 1811. *Political essay on the kingdom of New Spain* (Trans. by John Black) London, v. II, 377 p.

MENARD, H. W. 1955. Deformation of the northeastern Pacific basin and the west coast of North America. *Bull. Geol. Soc. America*, 66:1149-1198.

MINER, P. and L. 1954. Bahia Urvina, Isabela. *Commodores'Bull., Seven Seas Cruisings Assoc.* (Coronado, Calif.) No. 31, p. 13.

RICHARDS, A. F. 1954. Volcanic eruptions of 1943 and 1948 on Isabela Island, Galápagos Islandws, Ecuador. *Volcano Letter* (Hawaii), No. 525, p. 1-3.

RICHARDS, A. F. and R. S. DIETZ. 1956. Eruption of Bárcena Volcano, San Benedicto Is., México. *Proc. Eighth Pacific Sci. Congr., Phillipines*, II:157-176.

RICHARDSON, C. 1933. Petrology of the Galapagos Islands. *Bull. Bernice P. Bishop Museum*, 110:45-64.

SHUMWAY, G. 1954. Carnegie Ridge and Cocos Ridge in the west equatorial Pacific. *Jour. Geology*, 62:573-586.

SNODGRASS, J. M. and A. F. RICHARDS. 1956. Observations of underwater volcanic acoustics at Bárcena Volcano, San Benedicto Island, México, and in Shelikof Strait, Alaska. *Trans. American Geophys. Union*, 37:97-104.

U. S. HYDROGRAPHIC OFFICE. 1953. Notice to shipmasters. *Hydrographic Bull.*, No. 36:

— 1954. Ecuador. *Notice to Mariners*, Pt. I, No. 30, p. 1379.

WILLIAMS, H. 1952. Recent eruption on San Benedicto Island, Revillagigedo group, Mexico. *Volcano Letter* (Hawaii), No. 517, p. 7.

Reprinted from SCIENCE, April 24, 1959, Vol. 129, No. 3356, pages 1085–1087.

Wave-Riding Dolphins: How Do They Do It?

At present only the dolphin knows the answer to this free-for-all in hydrodynamics.

P. F. Scholander

One of the thrills of ocean travel comes with the sight of a school of dolphins speeding along through the waves. At more or less regular intervals the animals leap elegantly through the air, often the whole school in unison. These leaps, playful as they often seem, serve in fact their respiratory needs, for while the miniature whales are shooting through the air they complete in a split-second performance their exhalation-inhalation cycle.

Commonly, some individuals will part company with the school just to come dashing to the bow of the ship. An attentive observer leaning out over the railing can watch them speeding along close to the bow, and he may even hear them whistling together, while streams of bubbles escape from the blowhole; but unless already briefed, he is likely to miss the fact that the porpoises just seem to be "standing" there motionless, as if getting a free ride. This puzzling situation was pointed out by Woodcock (*1*), who gave his keen observations in the following words.

"Dolphins in the Gulf of Panama have been seen moving through the sea at a speed of ten knots, their entire bodies showing no apparent swimming motion. This performance was confined, in my observations, to the area immediately forward of the stem (prow) of a seagoing tug and to an estimated depth of one metre or less. Elsewhere near the bow, vertical oscillations of dolphins' tails were readily timed with a stop watch.

"When this 'motionless' swimming was first noticed, the animals were in the normal swimming position. In this position it was difficult to be sure that vertical motions of their tail surfaces were not occurring, since the direction of such motions would be nearly parallel with the line of sight of the observer. However, on several occasions dolphins were seen to turn on their sides during the 'motionless' swimming in such a position that their usual swimming motions would have been normal to the line of sight. No motion was visible in these animals, which were clearly seen just below the surface of the water. One animal remained on its side in this manner for 59 seconds, which represented a distance, at 5.15 m/sec. (10 knots), of 304 meters. At this time dolphins swimming near by used 1.9 tail oscillations per second in keeping pace with the vessel.

"These 'motionless' dolphins seemed to be riding the bow wave (that is, falling down the inclined surface). However, if dolphins are equal in weight to the weight of the water they displace, wave riding is not possible."

Buoyancy

Thus, it becomes necessary to find out about the buoyancy of these animals. Near the surface this depends largely upon the amount of air they carry in the lungs. Like other whales, they dive typically on inhalation and are then lighter than water (*2*), but, as pointed out by Woodcock and McBride (*3*), they have often been observed in aquaria to let out so much air while under water that they sink. The question then is: "Provided a porpoise exhales, will he become heavy enough under water so that he can plane or coast down a 15° wave slope at a speed of 10 knots, maintaining all the while his position in the wave?" It was established at Marine Studios, Florida (*3*), that a 200-pound porpoise, when dead and deflated, sank with a force of 9.2 pounds. The forward component at a 15° angle would amount to only 2.4 pounds, but on the basis of calculations of the drag, it was proposed that this slight force might still suffice for propulsion, provided the flow were laminar; if the flow were turbulent the force would be much too small.

While this explanation seemed severely limited in its application, the problem became even more challenging when Hayes (*4*) proposed that a porpoise would be propelled along in the front slope of a wave even when it was neutrally buoyant. By two different methods of calculating the hydrodynamic forces involved, he came to the conclusion that it is the total weight that matters and not the excess weight, and that the force available for propulsion would therefore be ample to overcome the drag, even if the flow were turbulent. This surprising solution was also given in the following general terms: "A third equivalent point of view is that an immersed body with no excess weight would be acted upon by a force which would give it the same acceleration as the fluid in the same vicinity." The validity of the latter formulation can hardly be doubted (compare the situation that particles accelerated in a centrifuge remain suspended unless they are heavier or lighter than the liquid), but as far as the wave-riding problem goes, this suggests Woodcock's idea rather than Hayes', for the acceleration in the front slope of a regular nonbreaking wind wave consists merely in a slow upward movement of the water. Only in the crest is the orbital movement of the water particles directed forward, but even so, their maximum velocity is only a small fraction of the wave velocity, commonly 10 to 12 percent, and only rarely exceeding 20 percent. In the trough the water moves backward; in the slope behind the crest, downward. If, therefore, one were to tow a streamlined body of neutral buoyancy within the wave, and at the velocity of the wave, one would expect to encounter drag in all positions, but slightly less in the crest than in the trough and an intermediate amount in the slopes—that is, the drag would simply reflect the relative velocities of the object and the water.

This was indeed found to be the case when two such objects of different shape and size were towed in the waves produced by a tug moving at 8 knots. It must readily be admitted that a fair evaluation of all the variables involved would call for rigorous testing in a tow-

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ing tank, but so far we have been unable to find evidence for the effect predicted by Hayes. It cannot be doubted, on the other hand, that a body sufficiently heavier than water could gravity-plane within the rising water of the front slope (like an aerial glider in an updraft), as suggested by Woodcock, and no doubt the reverse would also be true —namely, that a body lighter than water could "float-plane" within the falling water behind the crest.

Riding the Bow Wave

Whether or not one might find experimental support for these ideas on how to ride wind waves does not matter for our problem, for dolphins do not seem to ride wind waves, but only bow waves, and these are not necessarily identical propositions. On the contrary, it occurred to me, when Woodcock announced his interpretation, that there must be some other solution available, better than gravity-planing, because (i) porpoises regularly dive on inspiration, and are then lighter than water; and (ii) even if they were to exhale under water, the gravity vector for propulsion would be disproportionally small; moreover (iii), it seemed that an alternative explanation was at hand: the porpoise might be pushed forward by the bow wave, simply by putting its tail fluke at an angle into the upwelling water while planing its body horizontally in the ship-course, forward of the bow wave—that is, it would be picking up shear-force thrust with the fluke. This possibility avoids the buoyancy problem altogether and gives a propulsion in principle closely similar to that which the animal employs in a normal downstroke of its tail peduncle, as illustrated by Parry (*5*).

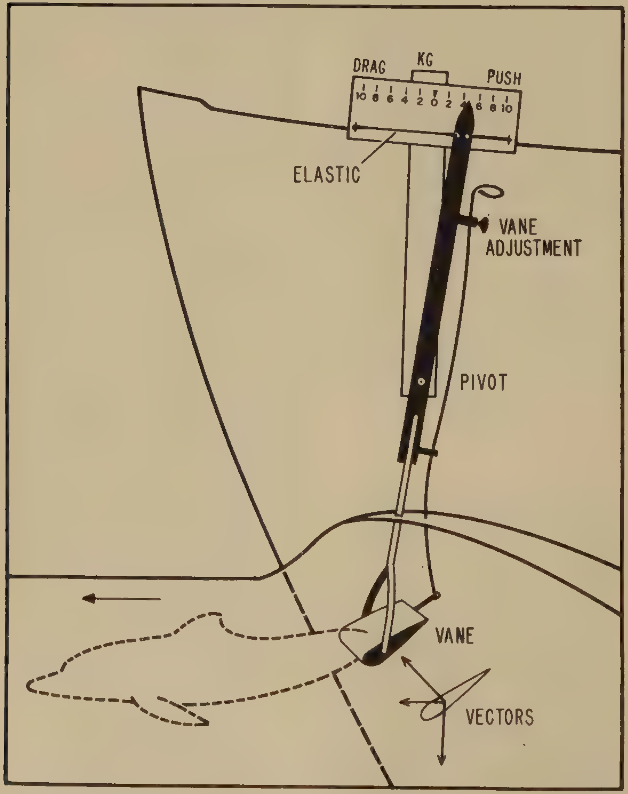

Fig. 1. Schematic presentation of the vane experiment. The relative height of the bow was about twice that shown in the drawing. The contour of an imaginary dolphin riding the bow wave is indicated.

Vane Experiment

While I was cruising in the quiet waters of a West Greenland fjord last summer on board the *M. S. Rundøy*, an opportunity was offered to test quantitatively this, by now, 10-year-old idea. The ship was equipped with a laboratory and machine shop. A streamlined vane was made, 20 by 40 centimeters in area and 4 centimeters at its thickest. It was suspended from a frame which was fastened onto the railing of the bow (Fig. 1). The vane could be clamped at any angle. Drag, or forward thrust, was measured by mounting the vane on a separate board which pivoted on the supporting frame. The board was spring-loaded and calibrated in either direction from a center position.

When the ship was going at 8 knots it was found that, as the vane was slanted downward at a 28° angle from the horizontal, it gave a considerable thrust forward, but on either side of this angle there developed a heavy drag. The forward thrust oscillated in step with the slight up-and-down pitching of the bow, from some 4 to 10 kilograms, averaging 7 kilograms. When we moved the whole gadget midships to a region of horizontal water and reset the vane, the minimum drag of our rather clumsy vane plus the submerged mounting averaged 12 kilograms. A "dragless" vane would accordingly produce a forward thrust of some 19 kilograms, and a real tail fluke of similar size but far more elegantly streamlined would hence be able to produce a thrust of some 18 to 20 kilograms at 8 knots' speed (*6*).

If, therefore, the porpoise, assisted by his pectoral fins, steers himself horizontally and "leans" his tail fluke against the upwelling water of the bow wave, he cannot help but be pushed along with the ship. As the water, in fact, is thrust not only upward and forward but also outward, he may ride keeled over on the side if he wishes. Moreover, as this mode of propulsion does not require that his lungs be empty, he need not take his ride in silence but may whistle to his fellow freeloaders as much as he deems fit. This, I believe, is the way dolphins ride the bow wave, and if it is not, they should try.

This scheme of picking up shear-force

thrust by the tail fluke suggests other possible ways of riding wind waves. If, for instance, the porpoise were cruising in the trough (or crest), he might be propelled along with the wave by sticking the tail fluke into the rising (or falling) water of the slope behind him. He could also combine shear-thrust riding with gravity- or float-planing. Since, however, these smart and playful animals evidently pay little attention to wind waves, this goes to show that none of our proposed ways of riding them can be practical. Evidently wind waves are not steep enough, and do not persist long enough, to do a porpoise much good. Only the abrupt and steep rise of a bow wave seems to be capable of giving him a worth-while push. But how does the porpoise produce the down-thrust of his tail fluke which he obviously needs in order to retain his position?

There appear to be other examples of bow-wave riding in the sea. Cousteau (*7*), in his book *The Silent World*, describes and shows a photograph of a tiny pilot fish which apparently rode the nose wave of a shark: "A thumbnail of a pilot fish wriggled just ahead of the shark's snout, miraculously staying in place as the beast advanced. He probably found there a compressibility wave that held him. If he tumbled out of it, he would be hopelessly left behind."

References and Notes

1. A. H. Woodcock, *Nature* 161, 602 (1948).
2. P. F. Scholander, *Hvalrådets Skrifter No. 22* (1940); L. Irving, P. F. Scholander, S. W. Grinnell, *J. Cellular Comp. Physiol.* 17, 145 (1941).
3. A. H. Woodcock and A. F. McBride, *J. Exptl. Biol.* 28, 215 (1951).
4. W. D. Hayes, *Nature* 172, 1060 (1953).
5. D. A. Parry, *J. Exptl. Biol.* 26, 24, Fig. 1 and plate 3, Fig. 9 (1949).
6. I wish to express my thanks to L. K. Coachman, O. Iversen, and H. Jensen for help in constructing and testing the bow-wave gadget. This part of the investigation was undertaken in spare time on the Arctic Institute Greenland Expedition 1958, which was aided by a contract between the Office of Naval Research, Department of the Navy, and the Arctic Institute of North America. At Scripps Institution of Oceanography I have enjoyed the benefit of discussions with W. H. Munk, and I had the able assistance of J. S. Kittredge and H. Andersen in the towing tests.
7. J. Y. Cousteau, *The Silent World* (Harper, New York, 1950).

The Relationship of the Juvenile Herring Stocks in Barkley Sound to the Major Adult Herring Populations in British Columbia[1, 2]

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ABSTRACT

During the summers of 1951–53, small body-cavity tags were inserted in 55,547 juvenile (1-year) herring on the lower west coast of Vancouver Island. Fifty of these tags were recoved from the catches of adult fish between 1953–54 and 1956–57. These recoveries indicated homing by sub-district (the region occupied by an adult population) to be 52% after two years at large, and 64% after three years. Comparable data for herring tagged as adults showed 82% and 81% homing respectively. The greater tendency for the immature fish to mix with other adult populations may result from the fact that these fish join adult schools when the latter are considerably dispersed and intermixed on the offshore feeding grounds. Thus, population studies linking the juvenile and adult stages may require the use of a larger basic unit of area than that encompassing the distribution of the adult population. The dimensions of this unit will depend on the local potential for intermixing of adult populations at the time of recruitment.

INTRODUCTION

On the basis of average differences in meristic characters and on the returns of fish tagged from the spawning stocks, it has been shown that the British Columbia herring resource consists of a limited number of more or less discrete populations (Thompson, 1917; Tester, 1937 and 1949; McHugh, 1954; Stevenson, MS, a). In addition, there are numerous small resident or local stocks which make up about 5% of the total stock. There are 10 major migratory populations and these show intermingling of about 25% on the average (Stevenson, MS, a), greatest intermingling occurring between populations whose spawning grounds, and presumably feeding grounds, are separated by the shortest distances.

For general fishery administrative purposes, the British Columbia coast has been divided into 3 *Districts* (and sub-divided into 29 *Areas* within these districts). Regions occupied by major herring *populations* have been designated as *sub-districts* (see Taylor *et al.*, 1957). These populations consist of *sub-populations* which intermingle to a greater extent than do the major populations.

The Barkley Sound herring stocks make up the major sub-population (about 80%) of the herring population in the lower west coast of Vancouver Island sub-district. This population spawns in coastal waters between Pachena Point and Esteban Point (Areas 23 and 24). The summer feeding grounds are believed to be located in open water near the entrance to the Strait of Juan de Fuca (Stevenson,

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[2] Based on part of a thesis accepted by the School of Graduate Studies, University of California, Los Angeles, in partial fulfilment of the requirements for the degree of Doctor of Philosophy. Contributions from the Scripps Institution of Oceanography, New Series, 1124

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MS, a). Tagging studies (Stevenson, MS, a) have shown that of the herring tagged on spawning grounds in this sub-district, 83% of the survivors return in the following year to spawning grounds in the same sub-district. Of the remainder, about 11% join the adjacent population along the upper west coast of Vancouver Island (a population of comparable size in Areas 25 and 26 whose summer feeding grounds are believed to be located off Nootka Sound and Esperanza Inlet) and 6% join the population belonging to the lower east coast of Vancouver Island (a larger population in Areas 17A, 17B, 18 and 19 which migrates through the Strait of Juan de Fuca to feeding grounds believed to be southwest of the entrance to the strait).

Studies of the population dynamics of herring in the juvenile stage were conducted in Barkley Sound from 1951 through 1954 (Hourston, 1958). Before the results of these studies can be applied with any confidence to the general picture, the relationship of juvenile stocks to the adult herring populations in this area must be established. In other words, to what extent are the spawning stocks in Barkley Sound recruited from the juvenile stocks reared there? In an effort to answer this question, tagging was conducted on juveniles immediately prior to their disappearance from inshore waters in the autumn months. Recoveries of tags were obtained from reduction plant magnets searching the catch of commercial-sized fish in later years.

ACKNOWLEDGMENTS

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TAGGING

TECHNIQUE

Juvenile herring larger than 70 mm in standard length were tagged with small body-cavity tags of nickel-plated iron with dimensions 13 × 3 × 0.5 mm. The tags were stamped in lots of about 500, with a series of four capital letters in different series for each lot. One to seven complete lots were inserted at each tagging, and the lot identification mark for each set inserted was recorded along with the date and place of tagging. Fish were captured by purse seine when near the surface at dawn or dusk. The seine employed was 37 fathoms long by 6 fathoms deep (68 by 11 metres) and was made of ¾-inch "cutched" netting, hung-in 20%. This size proved minimum for the capture of juveniles at this stage, and "cutching" the cotton was found to cause less abrasion to the fish than the use of other net preservatives of comparable effectiveness.

Methods of handling the juveniles and the equipment used therein were similar to those employed in marking juvenile herring and are illustrated elsewhere (Hourston, 1958). The captured fish were transferred into 5-foot deep live-pounds of half-inch tarred netting hung from a 3 × 4-foot frame of 4 × 4-inch lumber which floated on the surface. The bottom was held rigid by a similar-sized frame of half-inch metal pipe. Ropes attached to the four corners of the metal frame and drawn up through the corners of the wooden frame enabled the "drying up" of the pound to a shallower depth as the number of fish in the pound was reduced. During the tagging operation, groups of about 100 fish were transferred by dip net from the pound into a "tray" of half-inch cuprinoled netting joining 2 one-inch square "sticks" just over 4 feet long. These were set just inside one side of the pound and rested on the 4 × 4's forming either end of the pound's frame. By rolling the netting on to either stick, the desired depth of the tray could be obtained. The side of the pound with the tray along it was lashed to the side of the rowboat. One to three taggers sat in the rowboat facing lengthwise to the pound so that the tray was on their left side. A quick scoop of the left hand into the tray captured a fish in the palm of the hand.

The method of insertion was adapted from that used in tagging adult herring (Hart and Tester, 1934; Tester and Stevenson, 1947). The fish was held left side

TABLE I. Summary of tags inserted in juvenile herring.

	Number of tags			
Locality	1951	1952	1953	Total
Barkley Sound (Area 23)				
Banfield Inlet	1,400	4,198	2,091	7,689
Ecoole Cannery	...	2,064	...	2,064
Effingham Island	...	2,056	...	2,056
Pipestem Inlet	...	...	6,248	6,248
San Mateo Bay	...	6,017	3,147	9,164
Sarita Bay	...	...	5,157	5,157
Tzartus Island	4,164	...	...	4,164
Uchucklesit Inlet	5,809	3,986	1,538	11,333
Ucluelet Inlet	...	2,017	...	2,017
Total	11,373	20,338	18,181	49,892
Clayoquot Sound (Area 24)				
Dixon Bay	...	4,639	...	4,639
Steamer Cove	...	1,016	...	1,016
Total		5,655		5,655
Nootka Sound (Area (25)				
Nootka Cannery	...	1,940	...	1,940
Nanaimo Region (Area 17A)				
Departure Bay	...	...	8,437	8,437
GRAND TOTAL	11,373	27,933	26,618	65,924

TABLE II. Recoveries of tags inserted in juvenile herring in the lower west coast sub-district during 1951, 1952 and 1953. Place of recovery is sometimes in doubt because of mixing of herring catches at the plant. Probable localities of recapture are given in Roman type. Localities in italic type are possible, but are considered unlikely either because few fish were handled from that place on the day in question or, less often, because the place is remote from the point of tagging. Names of plants are coded as in Table V. The "adjusted number" associated with each recovery is a figure adjusted for plant efficiency in recovering tags and for the proportion of the catch searched for tags.

Years at large	Insertion		Recovery				
	Year	Place	Season	Place	Area	Plant	Adjusted number
LOWER WEST COAST SUB-DISTRICT							
1	1952	San Mateo Bay	1953–54	Effingham Inlet	23	NS	1.2
1	1952	Dixon Bay	1953–54	Sidney Inlet *Smith Inlet*	24 *10*	GG	1.1
1	1952	Dixon Bay	1953–54	Sidney Inlet *Uchucklesit Inlet*	24 *23*	PA	1.2
2	1951	Banfield Inlet	1953–54	Effingham Inlet	23	C	1.8
2	1952	Uchucklesit Inlet	1954–55	Barkley Sound	23	I	1.5
2	1952	Banfield Inlet	1954–55	Uchucklesit Inlet	23	I	1.5
2	1952	Banfield Inlet	1954–55	Barkley Sound	23	P	1.1
2	1952	San Mateo Bay	1954–55	Barkley Sound *Deepwater Bay*	23 *13*	C	1.2
2	1952	San Mateo Bay	1954–55	Barkley Sound	23	P	1.1
2	1952	Uchucklesit Inlet	1954–55	Barkley Sound *Nugent Sound*	23 *11*	P	1.1
2	1952	Uchucklesit Inlet	1954–55	Uchucklesit Inlet *Deepwater Bay*	23 *13*	I	1.5
2	1952	Banfield Inlet	1954–55	Barkley Sound	23	C	1.2
2	1952	Dixon Bay	1954–55	Uchucklesit Inlet	23	I	1.5
2	1952	Dixon Bay	1954–55	Barkley Sound *Quatsino Sound*	23 *27*	PA	3.4
2	1953	Banfield Inlet	1955–56	Barkley Sound *Swanson Channel*	23 *18*	I	1.9
2	1953	Banfield Inlet	1955–56	Barkley Sound	23	PA	1.7
3	1952	San Mateo Bay	1955–56	Effingham Inlet *Swanson Channel*	23 *18*	I	1.9
3	1952	Banfield Inlet	1955–56	Barkley Sound *Swanson Channel*	23 *18*	C	1.7
3	1952	San Mateo Bay	1955–56	Barkley Sound *Swanson Channel* *Nanoose Bay*	23 *18* *17A*	C	1.6
3	1952	Uchucklesit Inlet	1955–56	Effingham Inlet Barkley Sound	23 23	PA	1.7
3	1952	San Mateo Bay	1955–56	Barkley Sound *Swanson Channel*	23 *18*	I	1.9
3	1952	Steamer Cove	1955–56	Clayoquot Sound *Ououkinsh Inlet*	24 *26*	PA	1.7
3	1952	Dixon Bay	1955–56	Tofino Inlet	24	PA	1.7
3	1952	Dixon Bay	1955–56	Barkley Sound *Raymond Channel* *Deep Bay* *Swanson Channel*	23 *7* *14* *18*	C	1.7
3	1952	Dixon Bay	1955–56	Barkley Sound *Deep Bay* *Swanson Channel*	23 *14* *18*	C	1.7
3	1952	San Mateo Bay	1955–56	Effingham Inlet *Barkley Sound*	23 *23*	PA	1.7

TABLE II: *continued*

Years at large	Insertion		Recovery				
	Year	Place	Season	Place	Area	Plant	Adjusted number
			LOWER EAST COAST SUB-DISTRICT				
2	1952	Uchucklesit Inlet	1954–55	Swanson Channel	18	GG	1.7
2	1952	Uchucklesit Inlet	1954–55	Swanson Channel	18	GG	1.4
2	1952	San Mateo Bay	1954–55	Swanson Channel	18	NS	2.0
2	1952	Banfield Inlet	1954–55	Swanson Channel *Nanoose Bay*	18 *17A*	I	2.0
2	1952	Banfield Inlet	1954–55	Swanson Channel	18	C	1.1
2	1952	San Mateo Bay	1954–55	Swanson Channel	18	NS	2.0
2	1952	San Mateo Bay	1954–55	Swanson Channel *Nanoose Bay*	18 *17A*	I	2.0
2	1952	San Mateo Bay	1954–55	Swanson Channel	18	I	2.0
3	1952	Uchucklesit Inlet	1955–56	Swanson Channel Satellite Channel *Raymond Channel* *Barkley Sound*	18 18 *7* *23*	GG	1.4
3	1952	San Mateo Bay	1955–56	Satellite Channel Porlier Passage	18 17B	I	2.0
3	1952	San Mateo Bay	1955–56	Swanson Channel Trincomalia Channel Porlier Passage	18 17B 17B	GG	1.4
3	1952	San Mateo Bay	1955–56	Swanson Channel *Barkley Sound*	18 *23*	N	1.7
3	1952	Ucluelet Inlet	1955–56	Swanson Channel *Deepwater Bay*	18 *13*	PA	1.8
4	1952	San Mateo Bay	1956–57	Walker Rock	17B	C	3.6
			OTHER SUB-DISTRICTS				
2	1951	Uchucklesit Inlet	1953–54	Myers Passage	6	PE	1.7
2	1952	San Mateo Bay	1954–55	Deepwater Bay	13	I	1.4
2	1952	Effingham Island	1954–55	Quatsino Sound	27	P	1.4
3	1952	Dixon Bay	1955–56	Burnaby Passage *Thompson Bay*	2B(E) *7*	B	1.3
			SUB-DISTRICT OF RECOVERY UNCERTAIN				
2	1952	Banfield Inlet	1954–55	Barkley Sound Quatsino Sound	23 27	PA	. . .
2	1952	Ecoole Cannery	1954–55	?		NS	. . .
3	1952	San Mateo Bay	1955–56	Barkley Sound Swanson Channel Porlier Passage *Nanoose Bay*	23 18 17B *17A*	C	. . .
3	1952	San Mateo Bay	1955–56	Swanson Channel Porlier Passage Effingham Inlet Barkley Sound	18 17B 23 23	I	. . .
3	1952	Dixon Bay	1955–56	Swanson Channel Barkley Sound *Porlier Passage*	18 23 *17B*	GG	. . .
3	1952	San Mateo Bay	1955–56	Barkley Sound Swanson Channel Porlier Passage *Nanoose Bay*	23 18 17B *17A*	C	. . .

up across the palm of the hand with its head toward the tagger. (Tags were always inserted on the left side for convenience in searching for recoveries and inspecting for extent of healing of scars in any tagged fish returned undamaged.) Using half a pair of small scissors with the tip ground off to form a blade about 3 mm across, a vertical slit about 5 mm long was cut in the body wall through the second or third somite anterior to the insertion of the pelvic fins. The tag was then inserted through this slit and pushed forward toward the head into the body cavity with the tip of the tagging knife (Tester and Stevenson, 1947). The fish was then quickly returned to the water. The whole operation generally took less than 10 seconds. Fish that bled noticeably following the cut, or gave an appreciable jerk at the time the incision was made, were discarded.

INSERTIONS

Of the 65,924 tags inserted in juvenile herring during this study, 49,892 were inserted in Barkley Sound over a 3-year period (Table I). Small taggings were carried out in Clayoquot Sound in 1952 to extend coverage to the entire lower west coast sub-district and in the neighbouring upper west coast and lower east coast sub-districts in 1952 and 1953, respectively with a view to assessing immigration into the lower west coast sub-district.

In this paper, "age" refers to year of life nearing completion; e.g., a fish of "age III" is taken in the autumn or winter before its third "birthday".

TAG RECOVERY

TECHNIQUE

Recoveries of the metal body cavity tags inserted in the juveniles were made at various reduction plants where the catches are processed to meal and oil. After the fish are ground up, cooked and dried, the meal passes over a magnet which removes any metal objects, including tags, from the meal.

RECOVERIES

Five tags were recovered in the 1953–54 fishery, 22 in the 1954–55 fishery, 22 in the 1955–56 fishery and one in the 1956–57 fishery (Table II). The small number of recoveries is attributed mainly to a high tagging mortality.

Attempts were made to assess tagging mortality by experimental means. Six experiments conducted in various live tanks and pounds failed to yield a single survivor from 390 fish (mortality in the untagged "controls" varied from 8% to 51%). An approximate estimate of tagging mortality was, however, obtained by applying previously-estimated survival rates to adjusted tag returns and considering residual mortality to result from tagging (i.e., the whole tagging programme was treated as a mortality experiment). The procedure was as follows. Instantaneous natural mortality rates (q) have been estimated for this population at 0.20, 0.29, 0.39 and 0.48 for ages I–II, II–III, III–IV and IV–V, respectively (Hourston, 1958). The instantaneous fishing mortality rate (p) is estimated as 0.77 for ages

(942)

III–IV and IV–V (from $m = 0.54$, Stevenson, MS, b). The resulting total instantaneous mortality rates ($i = p + q$) give survival rates of $s = 0.82$, 0.61, 0.19 and 0.055 for ages I–II, I–III, I–IV and I–V (Ricker, 1948, appendix). Applying these survival rates to the adjusted returns (Table VII) of tagged fish, survivals from the 1951, 1952 and 1953 taggings were calculated as 0.04, 0.89 and 0.02%, respectively (Table III). On this basis, there were not enough fish used in the tagging mortality experiments to make it likely that even one fish would survive the tagging mortality—which is the result actually observed.

Because of the mixed catches processed in some plants, six of the tags recovered could not be assigned with reasonable degree of certainty to any area, or even sub-district: these recoveries were omitted from the analysis. However, in most cases, the preponderance of fish from one area, or the timing of deliveries from different areas, permitted probable assignments.

TABLE III. Recoveries of tagged juvenile herring at each age, adjusted back to time of tagging on the basis of average fishing and natural mortality subsequent to tagging, to show probable survival of the tagging operation. The unadjusted recoveries employed as a basis for their determination include those whose place of recovery is unknown, as well as those for which it is known, and are given in parentheses. (Adjustments are based on 69% efficiency in plant recovery of tags, 5% of the catch not searched for tags, and survival rates of 0.82, 0.61, 0.19 and 0.055 for ages I–II, I–III, I–IV and I–V respectively.)

Year-class	Number tagged	Recoveries					Probable survival of tagging
		II	III	IV	V	Total	
		no.	*no.*	*no.*	*no.*	*no.*	%
1951	12,373	...	5 (2)	...	...	5 (2)	0.04
1952	27,933	6 (3)	55 (22)	160 (20)	28 (1)	249 (46)	0.89
1953	26,618	...	5 (2)	...	...	5 (2)	0.02

The relative numbers of "certain" recoveries (i.e. sub-district of capture definitely known) and "probable" recoveries (i.e. tags recovered from plants processing mixed loads which were assigned, on the basis of the weight of the evidence, to a given sub-district) varied according to sub-district of recovery (Table IV).

TABLE IV. "Certain" and "probable" recoveries of tags inserted in the lower west coast sub-district, classified according to sub-district of recovery.

Type of recovery	Sub-district of recovery						
	Lower west coast	Upper west coast	Lower east coast	Middle east coast	Northern	Queen Charlotte Islands	All
Probable	26	1	14	1	1	1	44
Certain	13	1	11	1	1	0	27

The lower proportion of certain recoveries from the lower west coast sub-district may be traced to the fact that a larger portion of the catch from the area was processed in mixed loads than the catches from other sub-districts. Thus comparisons of percentage recovery by sub-district would be biased against the lower west coast sub-district if based on certain recoveries only. Consequently, probable recoveries were employed in the analysis.

INTERPRETATION OF RECOVERIES

Herring reduction plants differ in their efficiency in recovering tags. Also, a small portion of the catch is not searched for tags. Since these two sources of error are apt to apply disproportionately to different fisheries, they must be accounted for in any comparison at numbers of recoveries.

Losses due to failure of magnets to recover all the tags which enter the plants were assessed by putting a series of "test" tags in fish as they entered the plant and recording the percentage of these recovered at the magnets. The efficiency of plant magnets in recovering juvenile tags was tested in this manner during the 1953–54, 1954–55, 1955–56 and 1956–57 fishing seasons. (No tests were carried out in 1952–53 because of the relatively small fishery resulting from failure of the fishermen and the companies to reach an agreement on prices.) Most tests were run simultaneously with similar tests for the larger tags (19.4 × 4.4 × 1.6 mm) used on adult herring in order to provide a basis for interpretation of juvenile tag recoveries from adult tag recovery efficiency tests in plants where no tests were made with juvenile tags. Results for plants from which tags were recovered are given in Table V.

TABLE V. Summary of percentage efficiency of herring reduction plants in recovering test tags. Data are given only for plants and years in which tag recoveries were made.

Plant	1953–54		1954–55		1955–56		1956–57		
	Tests	Efficiency	Tests	Efficiency	Tests	Efficiency	Tests	Efficiency	Av. Efficiency
	no.	%	*no.*	%	*no.*	%	*no.*	%	%
Butedale (B)	...	...	...	...	1	80	...	...	80
Colonial (C)	3	57	2	85	2	60	1	30	61
Gulf of Georgia (GG)	1	90	3	60	3	80	...	...	73
Imperial (I)	...	...	2	70	3	53	...	...	60
Namu (N)	...	...	...	...	2	65	...	...	65
North Shore (NS)	3	87	2	40	...	...	...	...	68
Phoenix (P)	...	...	3	93	3	85	...	...	89
Port Albion (PA)	1	84	1	30	1	60	...	...	58
Port Edward (PE)	...	59[a]	...	...	...	...	...	...	...
All	8	75.3	13	67.6	15	69.6	1	30	69.2

[a] Calculated from 1953–54 efficiency in recovering adult tags, and the relative efficiency of recovering juvenile and adult tags in 1955–56.

Efficiency in recovering juvenile tags was extremely variable between plants (30–100%) and even within the same plant (40–92%). Differences in percentage recovery stem from (1) differences in the mechanical structure of the plant machinery, (2) differences in conscientiousness of plant crews and the pressure of their regular work, (3) the state of cleanliness of the machinery, and (4) the condition of the fish being processed. Because of the differences in plant efficiency, the average efficiency employed in correcting the number of recoveries may not represent conditions in the plant at the time the recoveries were made. However, the task of running frequent, regular tests in the plants was beyond the scope of this study. Adjustments were, therefore, applied for average differences between plants only. This should at least allow for continuous average differences in plant efficiency.

As compared with the larger "adult" tags run through at the same time, there was less time lag in the recovery of juvenile tags and the percentage recovery was about 10% less. The lower percentage recovery of juvenile tags may be due to a low return of those juvenile tags delayed in reaching the magnets. There is a greater chance for such tags to be permanently lost than for the larger adult tags. As the juvenile tags are lighter in weight than the adult tags they could be blown more readily through the driers, and hence the time lag in their recovery would be shorter. Also, they would have less of a tendency to drop through the meal and get lost in cracks and crevices. Another factor reducing overall recovery is the possibility that juvenile tags which reach the magnet would be more easily dislodged than the heavier adult tags.

A further adjustment is necessary to account for that portion of the catch which was not searched by magnets. Included in this category were landings not reduced to meal and oil, landings processed by plants which had no magnets or whose magnets were not operating at the time some loads were processed, and landings processed by plants for which no magnet efficiency tests had been made. Although this unsearched portion of the catch was relatively small, it varied appreciably from area to area. In order not to bias the results, adjustment factors were applied (Table VI).

TABLE VI. Tag return adjustment factors for the proportion of the catch searched by plant magnets.

	Statistical Area								
Year	2B(E)	6	13	17B	18	23	24	27	Average
1953–1954	...	1.00	...	...	...	1.03	1.03	...	1.02
1954–1955	...	...	1.00	...	1.11	1.03	...	1.30	1.11
1955–1956	1.00	...	...	1.08	1.08	1.00	1.00	...	1.02
1956-1957	...	...	...	1.08	...	...	...	...	1.08
All	1.00	1.00	1.00	1.08	1.10	1.02	1.02	1.30	1.06

RELATIVE HOMING OF JUVENILE AND ADULT HERRING STOCKS IN BARKLEY SOUND

Recoveries of juvenile herring tags were adjusted for plant magnet efficiency and proportion of the catch searched by magnets and were tabulated by subdistrict of recovery, number of years at large and year of tagging (Table VII).

TABLE VII. Recoveries (adjusted for plant magnet efficiency and proportion of the catch searched by plant magnets) of tags inserted in juvenile herring in the lower west coast sub-district during 1951, 1952 and 1953. The actual numbers of recoveries are given in parentheses. Percentage homing is given for each set of data.

		Sub-district of recovery							
Time at large	Year tagged	Lower west coast	Upper west coast	Lower east coast	Middle east coast	Northern	Queen Charlotte Islands	All	Percentage homing
years		*no.*	*no.*	*no.*	*no.*	*no.*	*no.*	*no.*	*%*
1	1952	3.5 (3)	... ...	... ...	... ...	... ...	... ...	3.5 (3)	100 (100)
2	1951	1.8 (1)	... ...	... ...	... ...	1.7 (1)	... ...	3.5 (2)	51 (50)
2	1952	15.1 (10)	1.4 (1)	14.2 (8)	1.4 (1)	... ...	... ...	32.1 (20)	47 (50)
2	1953	3.6 (2)	... ...	... ...	... ...	... ...	... ...	3.6 (2)	100 (100)
	All	20.5 (13)	1.4 (1)	14.2 (8)	1.4 (1)	1.7 (1)	... ...	39.2 (24)	52 (54)
3	1952	17.3 (10)	... ...	8.3 (5)	... ...	... ...	1.3 (1)	26.9 (16)	64 (62)
4	1952	... ...	... ...	3.6 (1)	... ...	... ...	... ...	3.6 (1)	0 (0)
Totals		41.3 (26)	1.4 (1)	26.1 (14)	1.4 (1)	1.7 (1)	1.3 (1)	73.2 (44)	56 (59)

The percentage homing as shown by fish at large for two and three years was compared to similar data on fish tagged as adults (Table VIII). (Data for fish at large one and four years were inadequate for further analysis.) Of the adjusted recoveries of herring tagged as juveniles, 52% homed to the same sub-district after 2 years at large and 64% homed after 3 years at large. Comparable estimates for herring tagged as adults were 82 and 81%, respectively. Estimates based on unadjusted recoveries showed similar differences. Thus the rate of emigration appeared to be about twice as great before maturity as that after maturity. Most of the fish that emigrated between the juvenile stage and maturity moved to the lower east coast populations whereas most of the emigrating adults joined the upper west coast stocks.

DISCUSSION

The greater tendency to wander on the part of the immature fish as compared to adults at large for a similar time interval may be related to their life history in the offshore stage. Juvenile herring move offshore at the end of their first summer and are not found again in quantity in inshore waters until they return as mature fish in the spawning stocks. The major populations have more opportunity for mixing on the offshore feeding grounds than during the spawning migration (Stevenson, MS, a). As the young herring mature, they join adult schools on their

TABLE VIII. Recoveries (adjusted for plant magnet efficiency and proportion of the catch searched by plant magnets) of tags inserted in adult herring in the lower west coast sub-district for categories for which comparable data is available for juvenile tag returns. The actual numbers of recoveries are given in parentheses. Percentage homing is given for each set of data.

Time at large	Year tagged	Sub-district of recovery: Lower west coast	Upper west coast	Lower east coast	Middle east coast	Upper east coast	Central	Queen Charlotte Islands	All	Percentage homing
years		*no.*	*no.*	*no.*	*no.*	*no.*	*no.*	*no.*	*no.*	*%*
2	1951	347.6 (311)	51.8 (10)	12.1 (10)	...	1.0 (1)	...	...	412.5 (332)	84 (94)
2	1952	25.9 (23)	5.5 (4)	10.9 (10)	2.2 (2)	...	2.5 (2)	...	47.0 (41)	55 (55)
2	1953	11.0 (10)	...	...	...	...	...	...	11.0 (10)	100 (100)
	All	384.5 (344)	57.3 (14)	23.0 (20)	2.2 (2)	1.0 (1)	2.5 (2)	... ...	470.5 (383)	82 (90)
3	1952	17.3 (14)	...	1.2 (1)	...	...	1.1 (1)	1.3 (1)	20.9 (17)	81 (82)

spawning migration. Presumably, once the newly-maturing fish have joined an adult school, they stay with it. Since the adult fish in the school have already spawned at least once, they may be less amenable to change in their migration route than the new recruits.

Under this proposed mechanism of recruitment to the adult stocks, more of the new recruits would be expected to return to their rearing region than to any other sub-district, since both young and adults move offshore from the same place and in the same direction. However, since adult populations intermingle somewhat on the feeding grounds, the maturing young would have ample opportunity to join schools from neighbouring sub-districts. The adult schools, although intermixed, would have had the experience of at least one spawning migration and may thus be better equipped to find their way back to a certain beach.

This theory of the mechanism of recruitment also accounts for the selective immigration on the part of the Barkley Sound juveniles. More of the lower west coast juveniles migrated to the lower east coast sub-district than to the upper west coast sub-district. In its spawning migration through Juan de Fuca Strait, the lower east coast adult population comes within 30 miles of the entrance to Barkley Sound and probably passes through, or very closely to, the feeding grounds of the lower west coast population off southern Vancouver Island. On the other hand, the major spawning grounds of the other adjacent population, that of the upper west coast, lie over 75 miles north of the major spawning grounds of the lower west coast population (Barkley Sound), and the feeding grounds might be separated by a comparable distance. Thus, recruits from the lower west coast spawnings would have more opportunity of joining the lower east coast spawning population than that of the upper west coast.

Mingling with more distant populations appears to be limited and is probably comparable to that of the adults.

In linking population studies on the juvenile and adult herring, it may therefore be necessary to consider a unit of area larger than that occupied by the adult population alone. The size of the unit may vary with the region, depending on the local potential for intermixing of adult populations at the time of recruitment. Population studies of this nature on the lower west coast of Vancouver Island probably should incorporate data from the lower east coast, but need not include data from the upper west coast.

REFERENCES

HART, J. L., AND A. L. TESTER. 1937. The tagging of herring (*Clupea pallasii*) in British Columbia: methods, apparatus, insertions and recoveries during 1936-37. *Rep. British Columbia Fish. Dept.* for 1936, pp. 55–67.

HOURSTON, A. S. 1958. Population studies on juvenile herring in Barkley Sound, British Columbia. *J. Fish. Res. Bd. Canada,* **15**(5): 904–960.

McHUGH, J. L. 1954. Geographic variation in Pacific herring. *Copeia,* 1954(2): 139–151.

STEVENSON, J. C. MS, a. The movement of herring in British Columbia waters as determined by tagging, with a description of tagging and tag recovery methods. 52 pp. plus figures and tables; summarized in *Rapp. et Proc.-Verb., Cons. Explor. Mer,* **140**(2): 33—34.

MS, b. Herring mortality at various stages in the life history. 17 pp. plus figures.

TAYLOR, F. H. C., A. S. HOURSTON AND D. N. OUTRAM. 1957. The status of the major herring stocks in British Columbia in 1955–56. *Rep. British Columbia Dept. Fish.* for 1956, pp. 45–77.

TESTER, A. L. 1937. Populations of herring (*Clupea pallasii*) in the coastal waters of British Columbia. *J. Biol. Bd. Canada,* **3**(2): 108–144.

1949. Populations of herring along the west coast of Vancouver Island on the basis of mean vertebral number, with a critique of the method. *J. Fish. Res. Bd. Canada,* **8**(7): 403–420.

TESTER, A. L., AND J. C. STEVENSON. 1947. Results of the west coast of Vancouver Island herring investigations, 1946–47. *Rep. British Columbia Dept. Fish.* for 1946, pp. 42–71.

THOMPSON, W. F. 1917. A contribution to the life history of the Pacific herring: its bearing on the condition and future of the fishery. *Rep. British Columbia Comm. Fish.* for 1916, pp. 39–87.

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YOUNG SCOMBROID FISHES FROM THE GULF OF MEXICO

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Inter-American Tropical Tuna Commission, La Jolla, California

ABSTRACT

Examination of some fish collections, made in the Gulf of Mexico from June, 1954 to August, 1956 by personnel of the United States Fish and Wildlife Service, have resulted in the separation and identification of young forms of several tuna and tuna-like species. These include the yellowfin tuna *(Thunnus argentivittatus)*, blackfin tuna *(Thunnus atlanticus)*, oceanic skipjack *(Katsuwonus pelamis)*, little tunny *(Euthynnus alletteratus)*, frigate mackerel *(Auxis thazard)*, and bonito *(Sarda sarda)*, as well as a few small specimens of *Thunnus* of indeterminate species. The methods of diagnosis employed are discussed, and some species are described and illustrated.

The capture of these young fishes indicates that several scombroid species spawn in the Gulf of Mexico at various times of the year.

INTRODUCTION

The United States Fish and Wildlife Service has been engaged for several years in an intensive survey of the fishery resources of the Gulf of Mexico and adjacent waters (Galtsoff, 1954). Numerous collections of fishes of the Gulf region have resulted from exploratory fishing and gear development work, conducted mainly from the Service research vessel M/V OREGON. Recently, we have had the opportunity to examine some of these collections from which we have been able to separate and identify young forms of several scombroid species. The present paper summarizes our methods and results.

We wish to thank Edgar L. Arnold, Jr., Harvey R. Bullis, Jr., George A. Rounsefell, and their associates in the Bureau of Commercial Fisheries, U. S. Fish and Wildlife Service, for the loan of the OREGON fish collections and the Director, Bureau of Commercial Fisheries, U. S. Fish and Wildlife Service, for permission to publish our findings. James E. Böhlke of the Academy of Natural Sciences of Philadelphia kindly permitted us to examine specimens from their accessions. We are also indebted to Mary Jane Fitzenkotter and Barbara M. Klawe, both of Mercy Hospital, San Diego, for preparations of microscopic sections, and to Ann Schleif and Robert L. Wisner of the Ocean Beach Medical Group and University of California Scripps Institution of Oceanography, respectively, for assistance in obtaining x-rays.

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METHODS AND MATERIALS

The material upon which our studies are based represents only a part of the collections of young tuna and tuna-like fishes made in the Gulf of Mexico by Service personnel between June, 1954 and August, 1956. We have not yet been able to examine other specimens known to have been taken on cruises of the OREGON during this same period, as well as those collections made prior to June, 1954 and subsequent to August, 1956. Detailed data for the stations listed in the sections on material examined are given by Springer and Bullis (1956) and supplementary sheets.

All specimens, which were preserved in formalin, were examined under a binocular microscope and were dissected, stained, sectioned, or x-rayed as necessary for identification. Gill-raker counts were made in each case from the first arch of the right side. Our measurements of total length represent the direct distance from the tip of the snout to the tip of the shortest median ray in the caudal fin.

We have followed, for convenience, the taxonomic nomenclature of Rivas (1951). However, it may be noted that Rivas (1954), following Ginsburg (1953), recognizes *Thunnus albacares* rather than *T. argentivittatus* as the correct name for the Atlantic yellowfin tuna. Also Rivas has placed the various tunas in the expanded family Scombridae.

RESULTS

Identification and description of young scombroids. There are present in all of the collections available to us a total of 1,256 young scombroid specimens among which we have tentatively identified the following genera and species: *Thunnus argentivittatus* (Cuvier), *T. atlanticus* (Lesson), *Katsuwonus pelamis* (Linnaeus), *Euthynnus alletteratus* (Rafinesque), *Auxis thazard* (Lacepede), and *Sarda sarda* (Bloch). In addition, a number of larval and juvenile forms were recognized as *Thunnus,* but could not be assigned to species, as will be discussed later.

Yellowfin Tuna, *Thunnus argentivittatus;* Blackfin Tuna, *T. atlanticus;* and *Thunnus sp. indet.*

Material examined. Thunnus argentivittatus: OREGON sta. 1088 (3,26-31 mm). *Thunnus atlanticus* OREGON st. 1088 (1,26), 1121 (4,28-34), 1134, (1,29), 1142 (1,25), 1178 (1,36), 1399 (1,26), Aug. 1956, 28°50′N, 87°50′W (4,25-37). *T. argentivittatus* or *T. atlanticus*: 1088 (1,19), 1121 (2,27-39), 1171 (1,19), 1360 (2, 5.5-8), 1367 (1, 23), 1399 (2, 15), Aug. 1956, 28°50′N, 87°50′W (11, 21-22).

We have 36 young tunas (*Thunnus*) ranging in total length from 5.5 to 39 mm. All were dipnetted under a night-light except two, the smaller individuals in the series, which were found in plankton net collections.

The two planktonic specimens which measure 5.5 and 8 mm, respectively, are difficult to identify because of their small size and early stage of development. However, the large size of the head relative to the rest of the body, the sharply pointed snout with well-developed teeth on the jaws, and the prominent pre-opercular spines indicate that these are indeed larval scombroids. The darkly pigmented first dorsal fins suggest that these fish are either *Thunnus* or *Euthynnus,* but the absence of chromatophores on the symphysis of the pectoral girdle and rami of the lower jaws establish their identity as young *Thunnus.* We are unable at this time to refer these very small specimens to species.

The remaining larger individuals were first examined externally for identifying features. One of the smaller juveniles (27 mm) was subsequently sectioned serially, and a larger individual (34 mm) was also dissected, to study the relative position of the internal organs which, for some species of tunas, is diagnostic. In addition, five specimens of various sizes were stained for bone study with alizarin red, using the techniques of Clothier (1950).

Our results indicate that all of these juveniles are young thunnids. Not only does their general appearance coincide with published descriptions and illustrations of young tunas but the vertebral formula for each individual is 18 (precaudal) + 21 (caudal) for a total of 39 vertebrae which is definitive of fishes of the family Thunnidae (Kishinouye, 1923; Godsil and Byers, 1944). Moreover, on our stained specimens, the anterior part of the lateral line is visible and its curvature in each case corresponds to that attributed to Thunnidae by Kishinouye (1923).

Specific identification of the larger juveniles was also attempted, but the difficulties attendant to this work were compounded by the knowledge that as many as five species of *Thunnus* may inhabit the Gulf of Mexico. They are the yellowfin tuna (*T. argentivittatus*), bluefin (*T. thynnus*), blackfin tuna (*T. atlanticus*), albacore (*T. alalunga*), and bigeye tuna (*T. obesus*). Of these, the albacore has been caught only off Jamaica and Hispanola in the western Atlantic Ocean (Bullis and Mather, 1956), while the bigeye tuna reaches the Atlantic coast of the United States (Mather and Gibbs, 1958). We have presumed that these two species are rare and most likely absent from the Gulf region. Certain anatomical features also exclude the possibility that our juvenile specimens are young albacore, provided the same arrangement obtains for Atlantic tunas as found by Godsil and Byers (1944) for Pacific species. Our microscopic sections show that the spleen is located on the right side of the body, in ventral view, whereas in albacore this organ is usually on the left side. The intestine also runs posteriorly on the right side of the abdominal cavity instead of along the left side as is characteristic of albacore.

A third alternative, *T. thynnus,* was eliminated because the first closed haemal arch of all of our specimens appears at the eleventh vertebra instead of at the tenth, which is reported to be typical of bluefin tuna (DeSylva, 1955).

The remaining two species are the yellowfin tuna (*T. argentivittatus*) and the blackfin tuna (*T. atlanticus*), both of which are common in the Gulf of Mexico (Bullis, 1955). While adult yellowfin tuna may be distinguished from adult blackfin tuna by such superficial characters as coloration, the best means of separation is the use of gill raker counts. DeSylva (1955) gives a gill raker range of 4-6+15-19, total 19-24, for *T. atlanticus* and 7-10 + 19-22, total 26-32, for *T. albacares* (=*T. argentivittatus*).

Rivas (1951, p. 222) has stated, "The young of *T. argentivittatus* and *T. atlanticus* are distinguishable with certainty only by gill raker count." The problem of identifying our small specimens, however, is not as simple or as definitive as Rivas has implied because we do not know for each of these species the size at which the full complement of gill rakers is attained nor the variation in number of gill rakers among individuals of the same size.

In order to examine these matters, we counted the gill rakers of 26 of our 34 young thunnids, ranging in size from 15 to 37 mm, for which gill rakers are observable. Complete counts for each specimen are given in Table 1. Also, in Figure 1, we have plotted the total numbers of gill rakers of each fish against its total length. The number of gill rakers increases steadily with size up to about 25 mm. Thereafter, the pattern is rather confused and we can discern two

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groups: individuals with gill raker counts from 19 to 22 and, at similar sizes, those possessing from 27 to 31 counts, with one individual having an intermediate count of 25. If we assume, as seems reasonable from a consideration of the counts from adult yellowfin and blackfin tuna previously given, that the range of variation between individuals of the same size and species is not likely to be as great as that exhibited by our specimens at sizes 26, 31, and 36 mm, we may conclude that we have representatives of not one but two species. Accordingly, we have provisionally identified as yellowfin tuna (*T. argentivittatus*) specimens no. 14, 22, and 25 of Table 1, all of which have the higher gill-raker counts and which, interestingly enough, were taken at the same station. The gill-raker counts of the remaining individuals of 25 mm length and larger, with one exception, fall within the range accorded blackfin tuna (*T. atlanticus*). The single

TABLE 1
Gill-raker Counts of Young Tunas, *Thunnus*, from the Gulf of Mexico.

Specimen no.	*Total length (mm)*	*Gill-raker Counts*				*Station no.*
		Upper arch	*Middle*	*Lower arch*	*Total*	
1	15	0	1	8	9	1399
2	19	1	1	12	14	1171
3	19	1	1	11	13	1088
4	21	3	1	10	14	*
5	21	3	1	11	15	*
6	21	1	1	12	14	1294
7	22	3	1	11	15	*
8	22	3	1	14	18	*
9	23	3	1	15	19	1367
10	23	4	1	14	19	1399
11	25	5	1	15	21	1142
12	25	4	1	15	20	*
13	26	5	1	16	22	1399
14	26	5	1	21	27	1088
15	26	4	1	16	21	1088
16	28	4	1	14	19	1121
17	29	4	1	16	21	1121
18	29	4	1	15	20	1134
19	30	4	1	15	20	*
20	30	4	1	15	20	*
21	31	4	1	15	20	1121
22	31	6	1	21	28	1088
23	34	4	1	14	19	1121
24	36	5	1	16	22	1178
25	36	7	1	23	31	1088
26	37	4	1	20	25.	*

*Station occupied during July, 1956 at 28°20′N., 87°50′W.

37 mm specimen with a gill-raker count of 25 is also tentatively diagnosed as a blackfin juvenile because of the upper arch count of four as compared to a count of seven for the 36 mm yellowfin tuna. Those individuals whose gill-raker counts could not be determined and those smaller than 25 mm may belong to either of these species. Further study of our material and the examination of additional specimens may help to resolve this problem of species identification, and we do not discount the remote possibility that species other than *T. atlanticus* and *T. argentivittatus* may be included among our very small specimens.

Figure 2 illustrates a 28 mm juvenile presumed to be a young blackfin tuna. We have found that pigmentation patterns are often quite useful in identifying small scombrids and have, therefore, outlined our observations for this particular specimen.

The first dorsal fin is heavily pigmented, but is not entirely black. A few faint chromatophores are visible at the anterior basal portion of the second dorsal fin, which is otherwise colorless. A darkly pig-

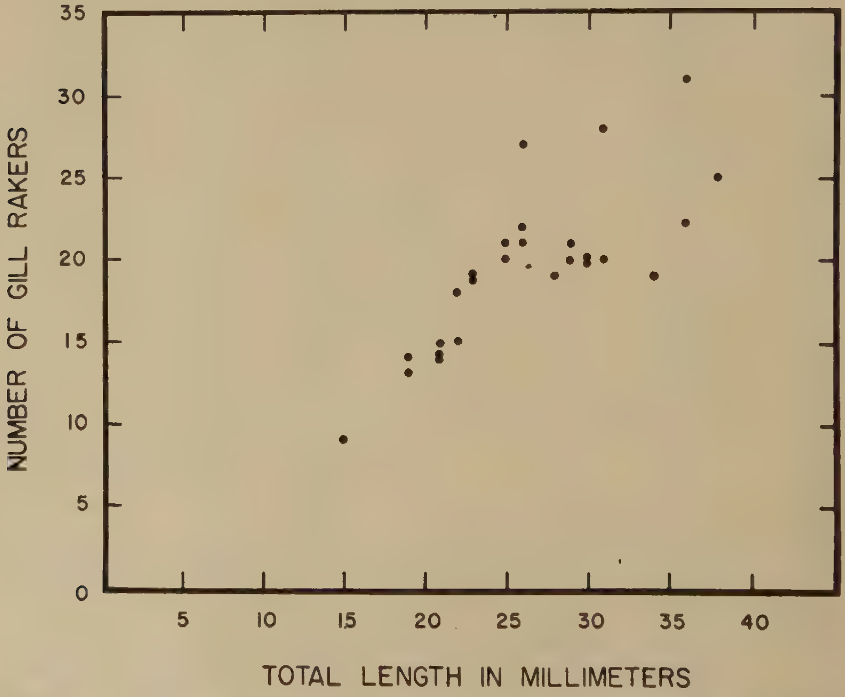

FIGURE 1. Gill-raker counts of young *Thunnus* plotted against total length.

mented area colors the top of the head and extends forward to the brain region. The dorsal portion of the body is heavily pigmented, but coloration does not extend caudally beyond the fifth dorsal finlet. A concentration of pigment is present along the lateral line and in some areas along the dorsal and lateral regions, resulting in a faint pattern of six vertical bars not unlike "parr" marks of young salmonids. Scattered chromatophores in the peritoneum are visible through the body wall, particularly in the abdominal region. The first ray of the pectoral fin is slightly pigmented and several large chromatophores are present on the operculum. The posterior margin of the orbit is pigmented and the tips of the lower jaw and snout are also colored. The portion of the snout between the two anterior nares is marked by scattered chromatophores. Some chromatophores appear at the base of the caudal fin, but are more concentrated in the upper half.

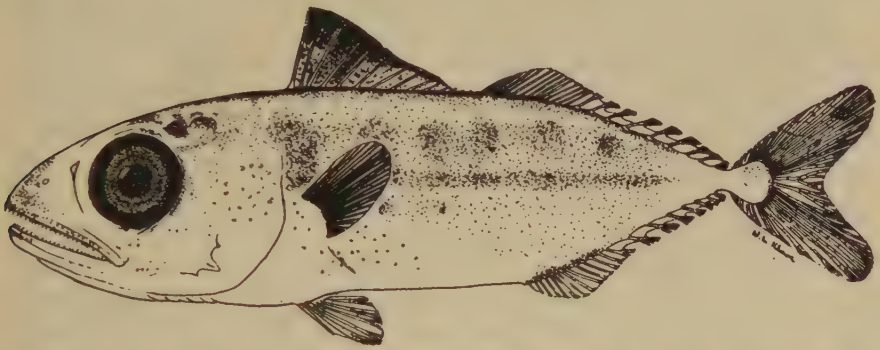

FIGURE 2. A 28 mm juvenile provisionally identified as a young blackfin tuna, *Thunnus atlanticus*, from OREGON station no. 1121, July 17, 1954.

As far as we have been able to determine, the coloration and general appearance of this juvenile is identical to that of specimens referred by us to yellowfin tuna. However, a slightly pigmented area is present on the inner surface of the operculum of all of our yellowfin specimens which is absent from those identified as blackfin tuna. This character may or may not be important.

Oceanic Skipjack, *Katsuwonus pelamis*

Material examined. OREGON sta. 1362 (1, 56), 1367 (2, 47-50), 1370(2, 29-45), 1378 (1,49).

This species is represented by six small specimens of total length 29 to 56 mm, which were collected by dipnet during 1955. All of these agree in description with that given by Schaefer and Marr (1948a) for juvenile *K. pelamis* collected by them in the Pacific Ocean, off Central America. Examination of a stained and cleared 45 mm individual and x-rays of three specimens, 49 to 56 mm in length, revealed the presence of a "trellis" formed by the fusion of the inferior foramen of the vertebrae and the haemal arches. This skeletal development is diagnostic of the family Katsuwonidae (Kishinouye, 1923; Godsil and Byers, 1944). The vertebral number of 41 (20 + 21), including the urostyle, further establishes the identity of our specimens as *Katsuwonus pelamis.* The genus *Euthynnus,* which also belongs to Katsuwonidae, is separable from *Katsuwonus* by its typically lower vertebral count of 39 or fewer (Kishinouye, 1923; Godsil, 1954).

Little Tunny, *Euthynnus alletteratus*

Material examined. OREGON sta. 1110 (4, 27-41), 1124 (4, 28-33), 1127 (86, 21-44; for details of capture see Bullis, 1955a), 1134 (3, 26-38), 1138 (2, 76-80), 1171 (38, 11-47), 1174 (4, 56-108), 1183 (5, 24-36), 1185 (29, 22-174), 1318 (10, 21-31), 1360 (4,3.5-5.3), 1362 (88, 30-53), 1367 (16, 31-55), 1368 (4, 6.2-8), 1370 (90, 29-65), 1372 (116, 4-80), 1374, (60, 17-68), 1378 (11, 49-86), 1380 (12, 32-94), 1399 (52, 24-49), 1477 (8, 19-29), Aug. 1956, 28°50′N, 87°50′W (33, 21-82).

The little tunny, *E. alletteratus,* is the best represented of all scombroid species in the OREGON material. There are on hand 679 individuals of sizes between 4 mm and 174 mm. This fairly good array of specimens greatly facilitated their indentification as *Euthynnus.* The following characters in particular were noted for the larger juveniles: (1) the presence of a skeletal "trellis" similar to *Katsuwonus* but within 39 vertebrae instead of 41 as in the latter, and (2) very long right lobe of the liver (Godsil, 1954). Larval forms were diagnosed from pigmentation (Matsumoto, 1958).

Euthynnus consists of three species, *E. alletteratus,* the little tunny of the Atlantic coast, *E. lineatus,* the black skipjack of the Pacific west coast, and *E. yaito,* the Hawaiian or Japanese black skipjack. Godsil (1954) has given a complete account of the characters which may be used to distinguish among these three species. Therefore, it may suffice to state that our specimens were assigned to *alletteratus* because of the presence of 39 vertebrae and the absence of vomerine teeth. Also, *alletteratus* is the only species known to occur in regions adjacent to the Gulf of Mexico.

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Gill rakers are considered a useful criterion for separating *alletteratus* from *yaito,* which is similar in appearance and structure. *E. alletteratus* has 37-40 gill rakers while *yaito* has a range of 29-33 (Godsil, 1954). However, as shown in Figure 3, where we have plotted the total gill-raker counts of each of three specimens, where available, selected at random for each size larger than 20 mm, this character appears to be valid for *E. alletteratus* only at sizes of about 60 mm or larger. At smaller sizes, other features need to be considered for the identification of *alletteratus* and their separation from related species.

As a point of interest, we note that Ehrenbaum (1924) in his early work described and figured what he thought might be the young forms of *E. alletteratus* but which, at the same time, he conjectured might well be those of the frigate mackerel *Auxis.* Our specimens at similar sizes do not correspond in shape or in pigmentation to those of Ehrenbaum and we are inclined to accept the identity of his specimens as *Auxis.*

Figure 4 (a, b, c) illustrates, respectively, a 4 mm, 6.5 mm, and 58 mm *E. alletteratus* from the Gulf of Mexico. The presence of a chromatophore in the region of the symphysis of the pectoral girdle,

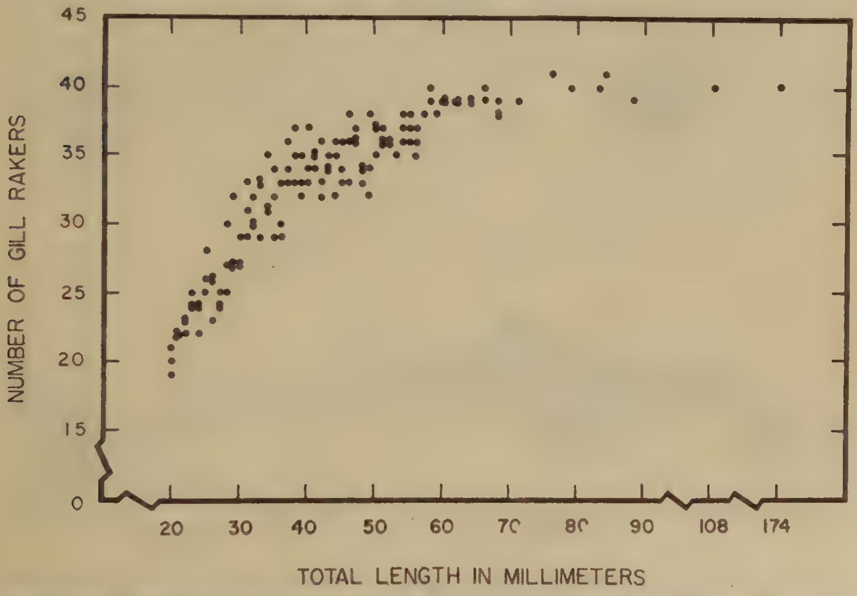

Figure 3. Gill-raker counts of young *Euthynnus alletteratus* plotted against total length.

as shown by our two small specimens, is characteristic of *Euthynnus* at these sizes. Chromatophores are usually found also along the mid-ventral line in the posterior region of the body and along the rami of the lower jaw. In the larger juveniles, vertical bars appear faintly along the dorsal region and number from six to nine in our specimens. This pattern does not appear to be confined to *alletteratus* but is exhibited by *E. yaito* and *E. lineatus* as well, judging from the descriptions and illustrations of Kishinouye (1923), Schaefer and Marr (1948b), Wade (1950), and Clemens (1956).

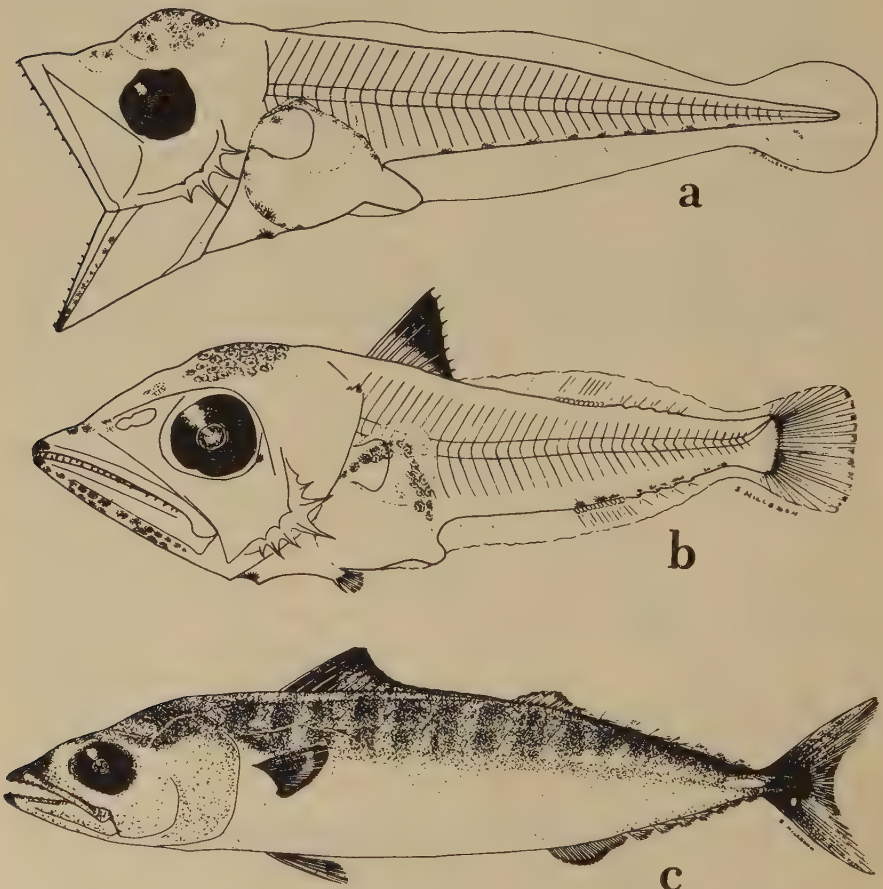

FIGURE 4. *Euthynnus alletteratus*. a. 4 mm specimen, OREGON sta. 1372, August 21, 1955. b. 6.5 mm specimen, OREGON sta. 1372, August 21, 1955. c. 58 mm specimen, OREGON sta. 1372, August 21, 1955.

Frigate Mackerel, *Auxis thazard*

Material examined. OREGON sta. 1088 (2,17-34), 1110 (34, 26-39), 1113 (8, 23-62), 1119 (2, 23-25), 1124 (1,30), 1127 (9, 22-27), 1134 (2, 45-49), 1139 (1, 46), 1171 (2, 14-25), 1174 (2, 65-110), 1183 (7, 21-33), 1185 (15, 21-145), 1318 (3, 20-25), 1360 (1, 5.5), 1362 (2, 38), 1370 (178, 26-56), 1372 (1, 40), 1374 (13, 28-40), 1378 (1, 97), 1380 (3,31-65), 1399 (99, 15-77), 1470(2, 65-74), 1477 (136, 15-52), 1492(7, 70-87), 1585 (1, 88), 1593 (1, 69).

We have among our collections 533 young frigate mackerel ranging in length from 5.5 to 145 mm. This cosmopolitan species is easily recognized by its body shape and by the separation between dorsal fins (Godsil, 1954). For larval forms, where the fins are not yet fully developed, pigmentation is an excellent diagnostic character as has been shown by Matsumoto (1958).

Godsil (1954), referring to the data of Fitch, has given the gill-raker formula of Pacific frigate mackerel as 9-12 + 1 + 30-36 for a total of 40-49. Postel (1956) found a range of 40-45 for five Mediterranean specimens. Our counts for Gulf of Mexico *Auxis* fall within the ranges given by these investigators, but we did not encounter any specimens approaching the upper limits of gill-raker numbers observed in Pacific frigate mackerel. Furthermore, as may be seen from Figure 5, where we have plotted the total gill-raker

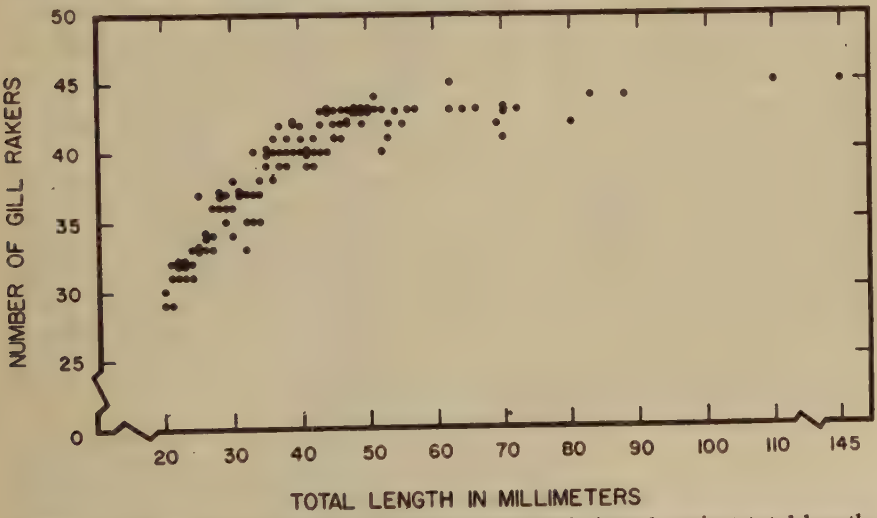

FIGURE 5. Gill-raker counts of young *Auxis thazard* plotted against total length.

counts of some of our specimens against corresponding total lengths in the same manner as previously for *Euthynnus*, the full complement of gill-rakers is not attained at sizes less than about 40 mm. Counts from adults, therefore, are not applicable to the identification of small specimens.

Bonito, *Sarda sarda*

Material examined. OREGON sta. 1470 (2, 64-67).

Two specimens of bonito are present in our collections from the Gulf. These measure 64 and 67 mm in total length; the latter appears in Figure 6. The presence of 20 spines in the first dorsal fin and a gill-raker count of 7 + 11 serve to identify these fish as young *S. sarda* (Rivas, 1951).

The bonito is common along the Atlantic coast of the United States and only recently has been found to occur in the Gulf of Mexico. Springer and Bullis (1956) report the capture of adults in the area of Arcas Bay (20°12′N, 91°59′W) in the southwestern Gulf region.

Spawning habits of scombroid fishes in the Gulf of Mexico. The collection and identification of larval and juvenile fishes not only provide useful taxonomic information but contribute importantly to the delineation of areas and seasons of spawning. In the latter application, the assumption is made that the presence of very young fish is indicative of recent spawning in an area at or near the time of capture. Such an inference may not be reasonable for those kinds of fishes for which the time of hatching of the egg is long, and the rate of growth of the young is slow, particularly in areas where the passive displacement of eggs and larvae by ocean currents may be fairly extensive. These factors, however, do not appear to constitute serious sources of error in the interpretation of our data because (1) the time of incubation of tuna eggs is thought to be short, about two days at most for some species (Schaefer, 1956), (2) young tropical tunas grow very rapidly (Clemens, 1956), and (3) velocities of surface currents in the Gulf of Mexico do not appear to be very great (Leipper, 1954). Nevertheless, we should note that our samples are not complete in time or space and that our deductions with respect to the spawning habits of the tuna and tuna-like fishes of the Gulf are, therefore, limited.

We have plotted in Figure 7 the localities of capture of the several species represented in our material for the purpose of indicating those areas within the Gulf of Mexico where spawning most likely occurs. Most of our specimens are from stations within a fairly well circum-

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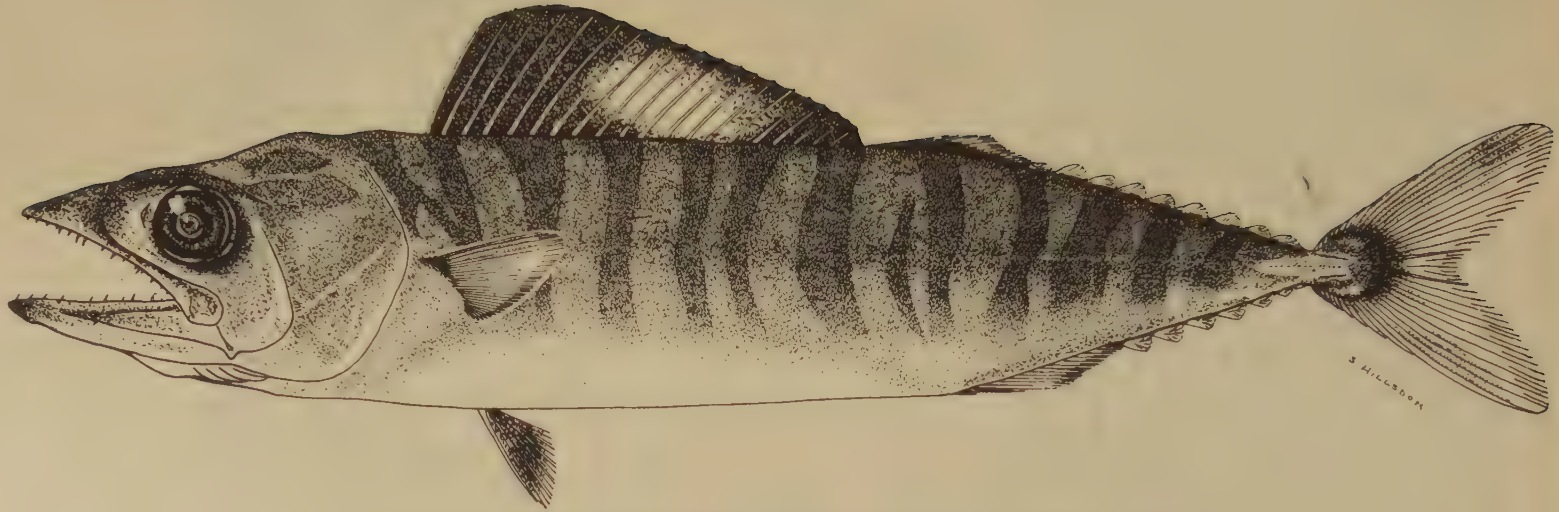
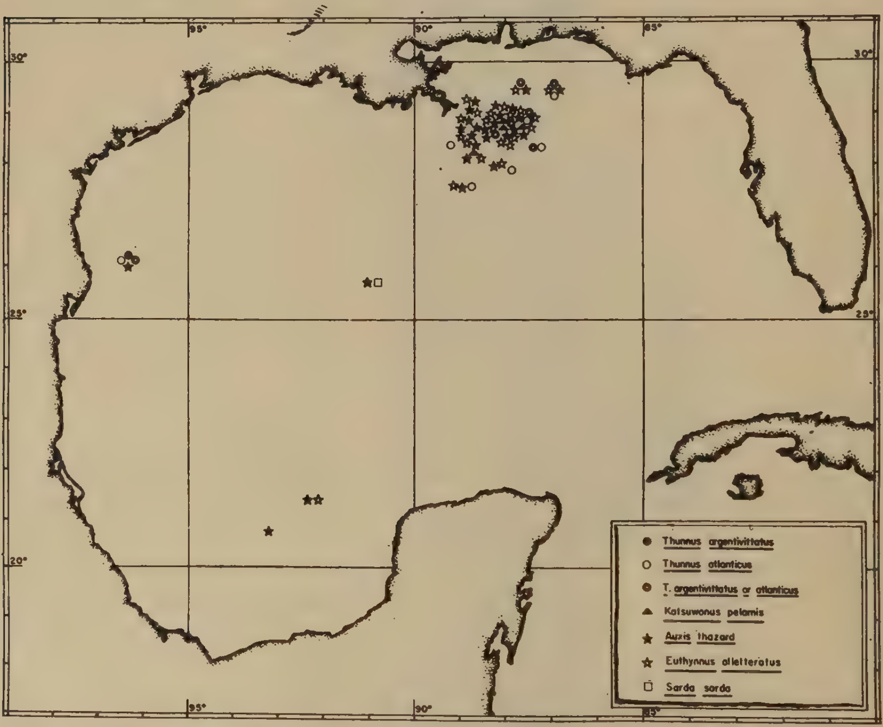


FIGURE 6. A 67 mm *Sarda sarda* specimen from OREGON station no. 1470, March 25, 1956.

scribed area southeast of the Mississippi River delta. This concentration relative to other areas may reflect sampling intensity rather than the distribution of young forms, but apparently the northcentral Gulf region is definitely a spawning locality for all of the species identified by us with the exception of the yellowfin tuna (*Thunnus argentivittatus)* and the bonito *(Sarda sarda)* which may also reproduce in this particular area. Specimens of the latter two species were taken only at single stations, in the northwestern Gulf and the central Gulf, respectively. However, while previous information on the spawning behavior of the bonito in the Gulf region is lacking, some data are available for yellowfin tuna. Bullis (1955b) reports the capture of sexually mature yellowfin tuna in the Gulf of Campeche and in the northern Gulf and the collections of young fish at widely scattered stations during the summer and early fall months. Therefore, this commercially important species probably spawns throughout the Gulf region.


95°
90°
85°
30°
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25°
25°
20°
95°
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● Thunnus argentivittatus
○ Thunnus atlanticus
● T. argentivittatus or atlanticus
▲ Katsuwonus pelamis
★ Auxis thazard
☆ Euthynnus alletteratus
□ Sarda sarda

FIGURE 7. Localities of capture of young scombroid specimens identified from some OREGON collections in the Gulf of Mexico from June, 1954 to August, 1956.

The widespread distribution of young frigate mackerel *(Auxis)* as shown in Figure 7 is not surprising in view of observations made in the Pacific (unpublished data) which show the species to be ubiquitous in its spawning.

The dates of capture (obtainable from Springer and Bullis, 1956) provide a basis for inferences as to the time of spawning of the several tunas and related species in the Gulf of Mexico. The months in which young forms were collected in some or all years represented in the OREGON collections are: *Thunnus argentivittatus*: June; *T. atlanticus*: June, August, September; *T. argentivittatus* or *atlanticus*: April, June, July, August; *Katsuwonus pelamis*: August; *Euthynnus alletteratus*: March, April, June, July, August; *Auxis thazard:* March, April, June, July, August; *Sarda sarda:* March. It appears from these data that from March through September, at some time or another, several tunas and their near relatives engage in reproductive activity. However, information presently available does not preclude the occurrence of spawning at other times of the year.

LITERATURE CITED

BULLIS, HARVEY R., JR.
1955a. Observations on schooling juvenile tuna, *Euthynnus alletteratus*, in the Gulf of Mexico. Copeia, 1955 (2): 153.

1955b. Preliminary report on exploratory long-line fishing for tuna in the Gulf of Mexico and the Caribbean Sea. Comm. Fish. Rev., *17* (10): 1-15.

BULLIS, HARVEY R., JR. AND F. J. MATHER, III
1956. Tunas of the Genus *Thunnus* of the Northern Caribbean. Amer. Mus. Novit., 1765: 1-12.

CLEMENS, HAROLD B.
1956. Rearing larval scombroid fishes in shipboard aquaria. Calif. Fish and Game, *42* (1): 69-79.

CLOTHIER, CHARLES R.
1950. A key to some southern California fishes based on vertebral characters. Fish Bull., Sacramento, *79:* 1-83.

DESYLVA, DONALD P.
1955. The osteology and phylogenetic relationship of the blackfin tuna, *Thunnus atlanticus* (Lesson). Bull. Mar. Sci. Gulf and Carib. 5 (1): 1-41.

EHRENBAUM, E.
1924. Scombriformes. Rep. Danish oceanogr. Exped. to Medit. and Adjacent Seas, Biology, *2* (8): 1-42.

GALTSOFF, PAUL S.
1954. Historical sketch of the explorations in the Gulf of Mexico. Fish. Bull., U.S., *55* (89): 3-36.

GINSBURG, I.
1953. The taxonomy and nomenclature of some Atlantic and Pacific populations of yellowfin and bluefin tunas. Copeia, 1953 (1): 1-10.

GODSIL, H. C.
1954. A descriptive study of certain tuna-like fishes. Fish Bull., Sacramento, 97: 1-185.

GODSIL, H. C. AND ROBERT D. BYERS
1944. A systematic study of the Pacific tunas. Fish Bull., Sacramento, 60: 1-131.

KISHINOUYE, KAMAKICHI
1923. Contributions to the comparative study of the so-called scombroid fishes. J. Tokyo Coll. Agric. Jour., *8:* 293-475.

LEIPPER, DALE F.
1954. Physical oceanography of the Gulf of Mexico. Fish. Bull., U. S., *55* (89): 119-151.

MATHER, FRANK J., III AND ROBERT H. GIBBS, JR.
1958. Distribution of the Atlantic bigeye tuna, *Thunnus obesus,* in the Western North Atlantic and the Caribbean Sea. Copeia, 1958 (3): 237-239.

MATSUMOTO, WALTER M.
1958. Description and distribution of larvae of four species of tuna in central Pacific waters. Fish. Bull., U. S., *58* (128): 31-72.

POSTEL, E.
1956. Donnees biometrique sur quelques Scombrides tunisiens. Bull. Sta. oceanogr. Salammbo, (53): 50-61.

RIVAS, LUIS RENE
1951. A preliminary review of the western North Atlantic fishes of the family Scombridae. Bull. Mar. Sci. Gulf and Carib., *1* (3): 209-230.
1954. A preliminary report of the spawning of the Western North Atlantic bluefin tuna *(Thunnus thynnus)* in the Straits of Florida. Bull. Mar. Sci. Gulf and Carib., *4* (4): 302-322.

SCHAEFER, MILNER B.
1956. Scientific investigation of the tropical tuna resources of the eastern Pacific. Papers presented at the International Conference on the Conservation of the Living Resources of the Sea (Rome, 18 April to 10 May, 1955), United Nations, New York, pp. 194-221.

SCHAEFER, MILNER B. AND JOHN C. MARR
1948a. Spawning of yellowfin tuna *(Neothunnus macropterus)* and skipjack *(Katsuwonus pelamis)* in the Pacific Ocean off Central America, with description of juveniles. Fish. Bull., U. S., *51* (44): 187-195.
1948b. Juvenile *Euthynnus lineatus* and *Auxis thazard* from the Pacific Ocean off Central America. Pacif. Sci., *2* (4): 262-271.

SPRINGER, STEWART AND HARVEY R. BULLIS, JR.
1956. Collections by the *Oregon* in the Gulf of Mexico. U. S. Fish and Wildlife Serv., Spec. sci. Rept. U. S. Fish Wildl. Serv., 196: 1-134.

WADE, CHARLES B.
1950. Juvenile forms of *Neothunnus macropterus, Katsuwonus pelamis,* and *Euthynnus yaito* from Philippine seas. Fish. Bull., U. S., *51* (53): 395-404.

(964)

Biological and Economic Aspects of the Management of Commercial Marine Fisheries

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Biological and Economic Aspects of the Management of Commercial Marine Fisheries

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ABSTRACT

Conservation management of the commercial marine fisheries has the general objective of maximizing man's long-term benefits from the exploitation of the fish resources. The question of what is most beneficial to man involves both biological and economic considerations. In this paper some of the effects of fishing on the fish stocks, and on the sustainable yields from them, are considered, together with important economic factors. It is indicated that the maximum sustainable average catch and the maximum net economic yield are mutually exclusive. It is possible, however, to obtain *some* net economic yield at the level of maximum sustainable harvest, but this requires some modification of the common property nature of fish stocks.

Conservation of the marine fisheries resources is a subject of interest to a great many members of this Society, and is a matter with which governmental agencies of the United States and various international agencies are much concerned. Conservation, in the modern sense, does not mean simply the preservation of a resource for the future, but also encompasses its use for man's benefit both in present and future time. It has often been said that "conservation is wise use." It may also be fairly stated that the objective of conservation management of commercial marine fisheries is to maximize man's long-term, continuing benefits from the exploitation of the fish resources. It is by no means clear, however, just what degree and kind of exploitation constitutes wisdom, nor which among possible alternatives is most beneficial.

I am certainly not going to attempt to answer these questions. But I think that it will be worthwhile to consider some of the fundamental biological properties of fish populations, and some of the principles of the economics of their harvesting, which should be taken into account in reaching the answers.

SOME BIOLOGICAL ASPECTS

Populations of marine fishes, in common with other living resources, differ from nonliving resources in an important respect; they are continuously renewed, and the rate of renewal depends on the size of the population which is left unharvested to produce new generations. A second important characteristic is that such populations tend to remain in dynamic balance, neither falling to zero nor increasing without limit. Over any reasonably long period of time, losses from the population must be balanced by accessions to the population. For a wide range of population sizes, when the percentage rate of loss is increased, decreasing the size of the population, from whatever cause, the percentage rate of renewal also increases, so that the population again comes into balance. This, of course, is the biological basis of fisheries, because from the standpoint of the fish the harvest taken by man is simply an additional source of mortality by predation, which is met by a compensatory increase in rate of population renewal, so that the population again comes into balance at some lower level of abundance at which increased rate of population growth balances the harvest taken by man. This must be so, else *any* continuing fishery would drive the population out of existence.

It may thus be seen that over a wide range of population sizes, and a correspondingly wide range of fishing effort, the population will come into dynamic balance, and a continuing harvest may be maintained. Although it is, theoretically, possible to impose such a large rate of predation on a fish population as to drive it below the level at which the self-regulating mechanism can bring it again into dynamic balance, to drive it below its threshhold level for survival, for commercial marine fisheries this is almost always below the level at which it is economically possible to fish. We are not often, therefore, concerned with preventing a commercial fish population from being exterminated. The problem is, rather, from among the range of fishing effort, be-

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tween zero and the maximum that is economically possible, to determine that which is optimal.

The general form of the relationship among amount of fishing, steady-state average population size, and magnitude of average sustainable catch, is known from the results of theoretical and experimental studies both of fishes and of other organisms, e.g. Nicholson (1954a, b), Ricker (1954), Lack (1954), and Silliman and Gutsill (1957), and from the data of important commercial fisheries (Buckmann 1938; Graham 1935, 1939; Schaefer 1954, 1957b; Beverton and Holt 1957, etc.), and may be illustrated as in Figure 1. With no fishing, the virgin population of fish of commercial sizes fluctuates about some size, L, which is the maximum which the environment will support under average conditions; there is no harvest. With the application of a little fishing effort, the population will come into balance at a magnitude somewhat below the virgin level, there will be a small harvest and the catch-per-unit-of-effort (which is proportional to population size) will be high. As the fishing effort increases, the steady-state population size decreases continuously, while the sustainable catch increases, but at a continually decreasing rate. At some intermediate level of fishing effort (labelled E_m on the Figure) there will be reached a maximum of sustainable total catch, after which the harvest actually decreases with increasing effort.

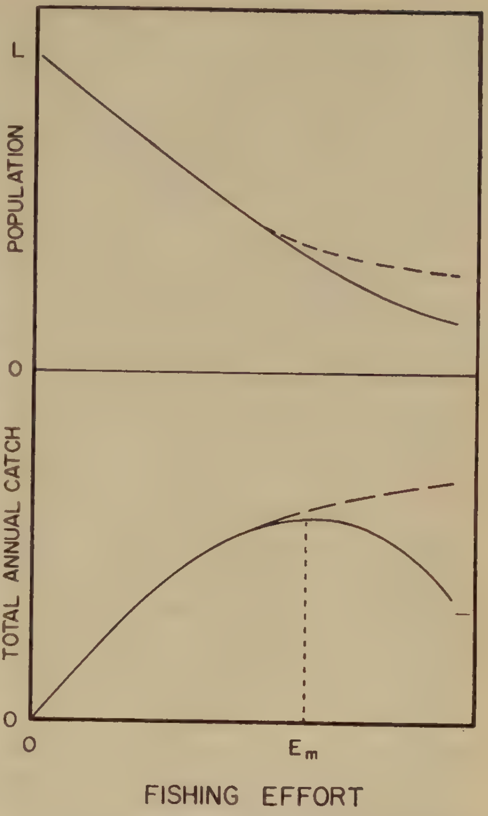

FIGURE 1.—General form of the relationship among amount of fishing, steady-state average population size, and magnitude of average sustained catch in a commercial fishery.

It should be noted that these are average relationships. Superimposed are fluctuations due to variations in fishery-independent (environmental) factors. These variations are often so large that it is difficult to estimate for particular fisheries the fishery-dependent relationships, and there are also important, short-term fishery management problems because of such variations.

It is biologically possible to have a sustained fishery at any of a wide range of fishing efforts. The problem is to decide which of these is most desirable. One possible choice is the level of maximum sustainable yield, E_m on the graph, at which the greatest poundage will be produced, on the average, in perpetuity. This has been explicitly chosen for particular fisheries (e.g. North Pacific halibut, tropical tuna) and has recently been adopted as a general objective by the International Conference on the Law of the Sea. Article 2 of the Convention on Fishing and Conservation of the Living Resources of the High Seas, adopted at that Conference, says, "As employed in this Convention, the expression 'Conservation of the living resources of the high seas' means the aggregate of the measures rendering possible the optimum sustainable yield from those resources so as to secure a maximum supply of food and other marine products." This choice is, however, not universal, because it is sometimes desired to take into account other qualities of the fishery.

Graham (1956) and Beverton and Holt (1957) have pointed out that it may be desirable to take into account the average size of the fish (which, in general, declines with increasing effort) and of other economic factors. The latter authors (p. 137 *et seq.*) also believe that if a fishery is managed by simultaneously controlling intensity of fishing and minimum size of fish to provide the greatest catch, so-called eumetric fishing, the curve of sustainable catch on effort has *no* maximum, but rises continuously toward an upper assymptote; this is illustrated by the broken line in Figure 1. If this be so, for fisheries which can be so managed, the choice of most desirable level of effort *must* be made on other (economic) grounds.

Even if the maximum sustainable average yield be chosen as the primary objective of fishery management, economic aspects of the fishery become important when it comes to the means by which the fishing effort shall be controlled. It is, therefore, important to consider some of the simple economic principles of commercial fishing.

SOME ECONOMIC ASPECTS

Fishermen are not fishing for fish, but for dollars. The amount of fishing is, therefore, largely determined by the value of the harvest and the cost of taking it. We need, then, to consider the nature of the relationships among fishing effort, value of catch, and cost of fishing effort.

The form of the value of catch as a function of fishing effort depends on the relationship between effort and quantity caught, illustrated in Figure 1, and, in addition, on the relationship between quantity and price. For most individual stocks of sea fish, the catch is a rather small share of the total production of all fish with which it competes in the market, and fish compete with other foods; consequently the price elasticity of demand is large, that is the price decreases little or not at all with increased landings. In these circumstances, the form of the production function (total value versus fishing effort) is similar to the relationship between effort and catch in pounds, and the maximum occurs at the same level of fishing effort (E_m), as has been shown by Schaefer (1957a). This is illustrated as the "value" curve in Figure 2. The value-per-unit-effort (or average return) falls off continuously with increasing effort as shown in the upper panel of the same Figure.

As to the cost of fishing, the unit costs are largely determined by the general economy, so that, to a good approximation, the cost-per-unit-effort is constant, and the total cost is proportional to the total effort. In Figure 2, I have drawn the cost-per-unit-effort lines in the upper panel, and the corresponding total cost lines in the lower panel, for three different levels of cost (C_1, C_2, and C_3), the significance of which I will come to in a few moments.

Now, fisheries resources, unlike most natural resources, are usually common property, being open to all comers on an equal footing. In consequence, so long as there is an opportunity to obtain more return to a unit of effort than its cost (including the normal return on capital investment, and a normal entrepreneur's fee) men will be attracted to the fishery, and it will tend to come to natural stability where the total value of the harvest is equal to the cost of taking it, and the average return is equal to the average cost. Thus, as has been described in detail by various authors, including Gordon (1953, 1954), Schaefer (1957a), and MacKenzie (1958), for the common-

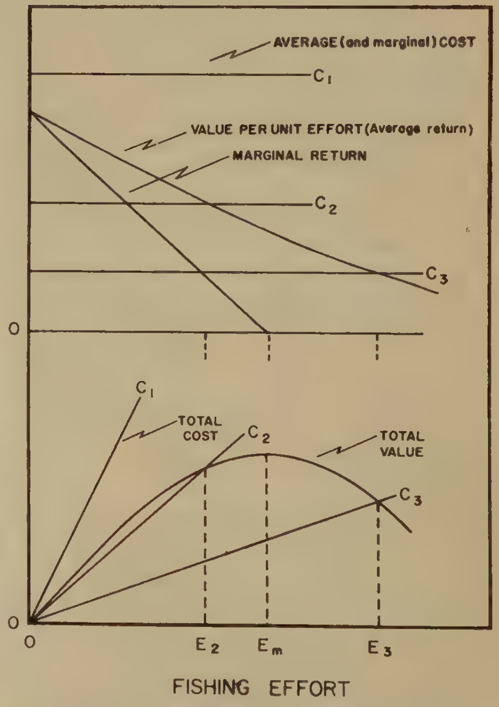

FIGURE 2.—Relationships among fishing effort, total value of catch, and total cost for three different levels of unit cost (lower panel); relationships among fishing effort, marginal and average return, and marginal and average cost (upper panel). See text for explanation.

property fish resource there can be no rental return to the resource, that is no net economic yield (the excess value of the harvest over cost of catching it).

The level of exploitation at which the unmanaged fishery will reach stability depends on the value of catch relative to the cost of effort. In Figure 2 are illustrated three possible situations, corresponding to an unutilized fish stock, an "underfished" fish stock and an "overfished" fish stock. In the first case, the cost of a unit of effort (C_1) is greater than the value-per-unit-of-effort, even at the virgin level of stock abundance. Here the fish are not worth catching. We know of many stocks in this condition, for example the Pacific coast hake and saury stocks. In the second case, the cost of a unit of effort (C_2) is such that it is equalled by the average return at a level of fishing effort (E_2) below that corresponding to maximum sustainable yield. Such a fishery is "underfished" if the criterion is maximum sustainable catch, and in this situation no restriction on fishing effort can produce a greater average harvest than is being obtained. In the third case, the cost of fishing effort relative to the value of catch is such that the cost-per-unit-effort is equal to the average return at a level of effort (E_3) *above* that corresponding to maximum sustainable yield. Such a fishery is commonly called "overfished," since the sustainable yield can be increased by restricting fishing effort.

It has been advocated by Gordon (1953, 1954) that the fisheries should be managed to produce maximum net economic yield, that is the greatest difference between total cost and total value of catch. This would be obtained where the tangent to the production function in terms of value is parallel to the cost line, i.e. where the marginal return is equal to the marginal cost. As shown in the upper panel of Figure 2, this is always at a lower level of effort than that which will be reached in the unregulated common-property situation, and is always at a lower level of effort and catch than that corresponding to maximum sustainable yield. Thus, maximum sustainable yield and maximum net economic yield are mutually exclusive. For "overfished" stocks it is, however, possible to obtain *some* economic yield at the level of maximum sustainable catch, i.e. the difference between the cost line, C_3, and the total value curve in the lower panel of Figure 2, by restricting the effort to E_m, *providing that the regulations are such that they do not increase the fishing costs.*

IMPLICATIONS FOR FISHERIES MANAGEMENT

In the case of "overfished" stocks it is possible, as seen from the foregoing theory, and as has been demonstrated in practice in a number of marine fisheries, to increase the abundance of the fish and the total catch by restricting the fishing effort. If the effort were restricted in such a manner as not to increase the fishing costs, there could also be obtained some economic yield. Regulations in practice, however, such as overall catch-quotas, closed seasons, and legislation against efficient gear, which limit the effort while allowing free access to the fishery by all comers, result in the cost of effort being increased so that all the possible economic yield is dissipated. This, indeed, can only be overcome by managing the fishery as a unit enterprise and thus, in one way or another, establishing at least a limited property right in the resources.

If it is deemed desirable to maximize the net economic yield rather than the sustainable harvest, this, of course, requires that there be established property rights in the fishery, whether these rights be in private hands or belong to governments. It also implies some choice between production of fish and profit from the fishery, since, as has been shown, the level of maximum net economic yield is always at a lower level of harvest than the maximum sustainable catch, and than the harvest obtained in the underfished common-property fishery.

The establishment of property rights in marine fisheries presents very great difficulties, even for the inshore stocks under the sovereignty of a single nation. For the high-seas fish resources, fished jointly by several nations, the problems are even more formidable. In the case of a few inshore bottom-dwelling organisms, such as clams and oysters, it has been accomplished. In these cases it is possible to have many individual property owners. Property rights in the inhabitants of the waters, however, the unit stocks of which are commonly large and occur over extensive areas, would have to be of large magnitude, raising problems of monoply if privately owned, and of socialized business if government owned. Even more difficult is the problem of the international nature of the high-seas resources. Since there are rather notable differences in the economies of different nations, it would seem practically impossible to reach agreement on the optimum level of fishing effort on economic grounds, and, even if that were possible, to decide the share of the fishery to be allocated to each nation. Beverton and Holt (1957, p. 395) are, however, apparently a bit more sanguine in the case of the North Sea at least. They say, "Here, in order to distribute equitably the benefits of regulation (to maintain the profit margin at a desirable level) among countries concerned, it is necessary only to agree on fixed ratios of fishing effort."

In any event, with the fuller utilization of the marine fisheries resources to meet the needs of the world's burgeoning population, it is certain that both the biological and the economic aspects of fisheries management will grow in importance, and that both aspects will need to be studied in detail as a guide to public policy with respect to these resources.

LITERATURE CITED

Beverton, R. J. H. and S. J. Holt. 1957. On the dynamics of exploited fish populations. U.K., Min. Agr. Fish and Food, Fish. Inv., Ser. 2, Vol. 19, pp. 1-533.

Bückmann, A. 1938. Ueber den Höchstertrag der Fischerei und die Gesetze organischen Wachstums. Ber. der Deutschen Wissenschaft. Komm. f. Meeresforschung, N.F., Vol. 9, pp. 16-48.

Gordon, H. S. 1953. An economic approach to the optimum utilization of fishery resources. Jour. Fish. Res. Bd. Canada, Vol. 10, No. 7, pp. 442-457.

———. 1954. The economic theory of a common property resource: the fishery. Jour. Political Economy, Vol. 62, No. 2, pp. 124-142.

Graham, M. 1935. Modern theory of exploiting a fishery, and application to North Sea trawling. Jour. Cons. Expl. Mer., Vol. 10, No. 3, pp. 263-274.

———. 1939. The sigmoid curve and the overfishing problem. Rapp. et Proc.-Verb., Cons. Expl. Mer., Vol. 110, pp. 15-20.

———. 1956. Concepts of conservation. Papers, Int. Tech. Conf. on Conservation of the Living Resources of the Sea, pp. 1-13.

Lack, D. 1954. The natural regulation of animal numbers. Clarendon Press, Oxford, 343 pages.

MacKenzie, W. C. 1958. Some economic aspects of control by quota. Canad. Fish Culturist, No. 22, pp. 21-24.

Nicholson, A. J. 1954a. An outline of the dynamics of animal populations. Austr. Jour. Zool., Vol. 2, No. 1, pp. 9-65.

———. 1954b. Compensatory reactions of populations to stresses and their evolutionary significance. Austr. Jour. Zool., Vol. 2, No. 1, pp. 1-8.

Ricker, W. E. 1954. Stock and recruitment. Jour. Fish. Res. Bd. Canada, Vol. 11, pp. 559-623.

Schaefer, M. B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bull., Inter-Am. Trop. Tuna Comm., Vol. L., No. 2, pp. 25-56.

———. 1957a. Some consideration of population dynamics and economics in relation to the management of the commercial marine fisheries. Jour. Fish. Res. Bd. Canada, Vol. 14, No. 5, pp. 669-681.

———. 1957b. A study of the dynamics of the fishery for yellowfin tuna in the Eastern Tropical Pacific Ocean. Bull., Inter-Am. Trop. Tuna Comm., Vol. 2, No. 6, pp. 245-285.

Silliman, R. P. and J. S. Gutsill. 1957. Response of laboratory fish populations to fishing rates. Trans. Twenty-second North Am. Wildlife Conf. (1957), pp. 464-471.

Geochimica et Cosmochimica Acta, 1959, Vol. 17, pp. 201 to 208. Pergamon Press Ltd. Printed in Northern Ireland

Some aspects of the marine geochemistry of uranium

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Abstract—The uranium concentrations in marine calcareous material of a biological origin varied between 0·0X and 0·X p.p.m. with the exception of corals which had concentrations of several p.p.m. The aragonitic oolites and aragonite precipitated from sea-water had values similar to those of the corals. A geochronology based on the growth of ionium (thorium-230) from uranium is applicable not only to corals, as previous investigators have pointed out, but also to oolites. Several examples of "oolite ages" are given. The uranium content of ferromanganese minerals from pelagic deposits is of the order of from 4 to 5 p.p.m.

Several problems concerned with our studies on marine sediments have prompted investigations of the uranium contents of various oceanic mineral deposits. First of all, it was of interest to ascertain what extensions of the uranium–ionium dating technique applied by Barnes *et al.* (1956) to corals might be found in other carbonates of the marine environment. Secondly, the ionium/thorium chronology for pelagic sediments developed by Goldberg and Koide (1958) demands a knowledge of the uranium content of the sample under consideration in order to know the amount of uranium-supported ionium. Finally, an extended knowledge of the distribution of uranium among the components of marine sediments is of general utility to the marine geochemist.

Experimental

Uranium assay of calcareous samples

An amount of sample containing at least 0·5 μg of U is dissolved in concentrated nitric acid. Any organic matter is destroyed by the addition of concentrated perchloric acid, followed by heating to perchloric acid fumes. Ferric iron (10 mg) is added to the diluted acid sample to carry down any uranium on a ferric hydroxide floc formed by the addition of gaseous ammonia. The precipitate is converted to a sulphate solution, which is the most satisfactory form for the uptake of uranium in the subsequent anion-exchange process, by the addition of concentrated sulphuric acid.

The pH is then adjusted to a value between 1·0 and 1·5 with 5 M sodium hydroxide. A sufficient amount of 6% sulphurous acid is added to completely reduce the ferric iron to the divalent state, a form which does not adhere to the ion-exchange column. The solution is then passed through an IRA 400 (80-100 mesh) resin in the sulphate form at a rate of approximately one drop per second with the resulting adsorption of uranium on the column (Fisher and Kunin, 1957). The column is subsequently rinsed with 50 ml of a 0·1 M sodium sulphate solution containing 5 ml of 6% sulphurous acid and then with 50 ml of hot water.

The uranium is eluted with 40 ml of hot 1 M perchloric acid into a 50 ml beaker and then the eluant is evaporated to fumes of perchloric acid. At this

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point 2 ml of concentrated nitric acid are added and the solution evaporated to dryness. (These last steps destroy any organic matter taken up by the eluant from the resin.) The residue is taken up in 1 ml of 25% HNO_3, transferred to a 10 ml volumetric flask; the beaker is rinsed with 4 ml of water which is added to the flask, followed by the addition of 1 ml of 0·1 M ammonium tartrate, 1 ml of 0·2% EDTA and 3 ml of the reagent solution (0·2 g of dibenzoylmethane dissolved in 300 ml of redistilled pyridine). The absorbance is measured at 415 mμ against a reagent blank, in 10 cm cells 30 min after the addition of the reagents (Yoe *et al.*, 1953).

Table 1. Uranium analyses on Mississippi limestone

Sample	Uranium found
1	1·11
2	1·07
3	1·07
4	1·09
5	1·04
6	1·02
7	1·06
8	1·09
	Average value 1·07 ± 0·03

Other results (Sackett, 1958)

Fluorimetric method	1·02 ± 0·05
Activation analysis	1·07 ± 0·05
Isotope dilution	1·04 ± 0·06

The EDTA solution was used to mask any trace amounts of iron that might have been carried through the procedure or picked up while the tartrate solution was added to prevent the development of any zirconium (or hafnium) dibenzoylmethane colour, especially in the case of ferromanganese minerals which contain an appreciable amount of zirconium.

Pyridine was used in the final step both as a pH buffering agent and also as a solvent for the dibenzoylmethane. Previous workers have encountered pH adjustment difficulties in this colorimetric technique which can be eliminated by the use of pyridine. The "measured pH" in the final solution was 5·85 ± 0·05.

Uranium assay of ferromanganese minerals

An amount of sample containing at least 0·5 μg of U is dissolved in concentrated hydrochloric acid and any residue is removed by centrifugation. The iron is precipitated as the hydroxide upon the addition of gaseous ammonia to the solution and the resultant precipitate is dissolved in nitric acid. A second iron hydroxide precipitation is made and the precipitate again is taken up in nitric acid (0·7 ml) and diluted with 10 ml of water. Ammonium nitrate is then added

(19 g) as a salting-out reagent and the uranium is extracted twice into 10 ml portions of ethyl acetate. The ethyl acetate solution is evaporated to dryness, the residue taken up with sulphuric acid, fumed and the resultant solution is carried through the ion-exchange resin as above.

Accuracy and precision of the results

Analyses were made on a Mississippi limestone, previously used by Professor H. A. POTRATZ of Washington University, as a standard in his uranium work. Table 1 gives values found in this and other laboratories.

In the analyses of calcareous materials a precision and accuracy of plus or minus 5 per cent was realized. However, results on the ferromanganese minerals are undoubtedly less accurate owing to the ethyl acetate extraction step which is not 100 per cent efficient. The use of U^{233} as a yield tracer would certainly refine these analyses. Owing to the fact that low level α-counting and processing was going on in the same laboratory, advantage was not taken of this technique.

RESULTS

The uranium contents of a group of calcareous organisms are given in Table 2 along with the crystal form of the shell. Table 3 gives the uranium concentrations in a series of oolites, an aragonitic deposition of calcium carbonate, apparently of a non-biological nature. Two corals, *Diploria labrinthiformis* and *Montastrea annularis*, collected at Windleys Key, Florida, are included for comparison. Both of these species are mixtures of calcite and aragonite. Probably, aragonite was originally laid down by the animals, inasmuch as modern specimens analysed pure aragonite. The conversion was apparently accompanied by the loss of uranium and/or ionium, as the uranium–ionium ages for these corals differ by nearly a factor of 2 (see Table 3 and accompanying text) and the samples were taken from the same 6 ft block of essentially one single age (GINSBURG, personal communication).

Uranium analyses were also made upon calcium carbonate samples precipitated from sea-water, which was previously filtered, and these results are collected in Table 4. These samples were all aragonite. Finally, in Table 5, are listed the uranium contents of some manganese nodules from both the Atlantic and Pacific Oceans.

DISCUSSION

The uranium concentration in marine oolites (average value of 3 p.p.m.) compares favourably with the values found in the laboratory precipitation of aragonitic calcium carbonate. This result provides another argument for the inorganic origin of these calcareous sands (a review of this problem may be found in REVELLE and FAIRBRIDGE, 1957; recent investigations by LOWENSTAM and EPSTEIN, 1957, on the isotopic analyses of carbon and oxygen in carbonates from the marine environment also point to a non-biological origin of oolites). Further, the high uranium values in corals (2·9–5·5 p.p.m.), initially observed by BARNES *et al.* (1956), are confirmed in two further cases.

These results parallel to some extent the accumulation of strontium in marine

Table 2. Uranium contents of marine calcareous specimens

Sample	Class	Location	Uranium (p.p.m.)	Crystal type
Dendraster excentricus	Echinoidea	La Jolla, Calif.	0·17	Calcite
Dendraster laevis	Echinoidea	South Coronada Isle, Mexico	0·18	Calcite
Tetraclita squamosa	Cirripedia	La Jolla, Calif.	0·041	Calcite
Protothaca staminea	Pelecypoda	La Jolla, Calif.	0·21	Aragonite
Littorina planaxis	Gastropoda	La Jolla, Calif.	0·012	Aragonite
Acmeca limatula	Gastropoda	La Jolla, Calif.	0·067	Aragonite
Olivella biplicata	Gastropoda	La Jolla, Calif.	0·022	Aragonite
Littorina scutulata	Gastropoda	La Jolla, Calif.	0·028	Aragonite
Trochus niloticus	Gastropoda	Outer reef, Palau	0·009	Aragonite
Mytilus edulis	Pelecypoda	Dutch Harbor, Alaska	0·046	Arag. + calcite
Mytilus californianus	Pelecypoda	La Jolla, Calif.	0·021	Arag. + calcite
*Pseudochama**	Pelecypoda	La Jolla, Calif.	0·013	Arag. + calcite
Haliotis corrugata	Gastropoda	La Jolla, Calif.	0·013	Arag. + calcite
Haliotis cracherodii	Gastropoda	La Jolla, Calif.	0·014	Arag. + calcite
*Bryozoa**	Bryozoa	On the surface of Haliotis corrugata	0·47	Arag. + calcite
Tegula fonebralis	Gastropoda	La Jolla, Calif.	0·004	Arag. + calcite
Acathina spirata	Gastropoda	La Jolla, Calif.	0·032	Arag. + calcite
Ianthina	Gastropoda	Open Pacific Ocean	0·044	Arag. + calcite
Diploria labrinthiformis	Anthozoa	Key Largo Limestone, Windleys Key, Florida	2·5	Aragonite
Montastrea annularis	Anthozoa	Key Largo Limestone, Windleys Key, Florida	3·2	Aragonite

* Contained detrital sand and/or silt particles.

calcium carbonates. Oölites contain somewhat above 2 per cent strontium carbonate (LOWENSTAM and GOLDBERG quoted in REVELLE and FAIRBRIDGE, 1957) likewise the aragonite precipitated from sea-water in our laboratory contains an identical amount of $SrCO_3$. THOMPSON and CHOW (1955) summarize similar findings of strontium carbonate concentrations in corals from work in their own and other investigators' laboratories.

Whereas strontium is much more readily accommodated in the aragonitic as opposed to the calcitic structure (THOMPSON and CHOW, 1955) in biological calcareous specimens, the uranium in our limited set of analyses does not seem to show such an evident preference (excluding of course the corals).

The presence of substantial amounts of uranium in the oölites directed this investigation to the possible use of these minerals in age determinations by the uranium–ionium parent–daughter relationships. Such a chronology would be

Table 3. Uranium and ionium contents and "U-Io ages" of oolites

Sample	Uranium (p.p.m.)	Thorium (p.p.m.)	Ionium (uranium equivalents)	Age (years)
Bahamas Banks North of Joulters Cay in area of submarine sand channels and deltas; 30-50 mesh fraction.	3·3	n.d.*	0·00	Recent
Laguna Madre LM-193B, from API 51 project; $\frac{1}{4}$-$\frac{1}{2}$ mm fraction. Sample contained a residue of 21·3% quartz and feldspars after acid dissolution.	0·83	2·0	0·92	—
Bahama Bank, about 1 mile SE of South Point, Cat Cay; 79°15′ W; 29°30·5′ N.	3·4	n.d.	0·00	Recent
Bahama Bank, 2 miles S of South Cat Cay,	3·1	n.d.	0·23	9,000
Miami, dredged from below sea level in Topine Brothers Rock Pit on Stock Island, near Key West.	3·8	n.d.	3·4	260,000
Friable oolite from a soil horizon in Queens Staircase, Nassau, N.P.	3·5	n.d.	2·6	160,000
Great Salt Lake, Stansbury Point, quartz residue of 6·8%, following acid dissolution.	5·8	1·2	1·3	—
Coral, Key Largo Limestone, *Montastrea annularis.*	3·2	n.d.	2·1	130,000
Coral, Key Largo Limestone, *Diploria labrinthiformis.*	2·5	n.d.	2·0	230,000

* n.d., not detected; less than 0·05 p.p.m., see text.

Table 4. Uranium in calcium carbonates, aragonitic, precipitated in the laboratory from sea-water

Sample	Uranium in $CaCO_3$ (p.p.m.)
1. CO_2 passed through water under heat treatment; following cooling, NH_3 is passed through the system. Final pH = 7·6. A small amount of calcium sulphate contaminated this sample.	2·6
2. Similar to above but final pH was 7·9.	3·2
3. Similar to above but final pH 7·95. Sample (1), $CaCO_3$ floating at surface	3·2
Sample (2), $CaCO_3$ adhering to walls of vessel.	4·6

Table 5. The uranium contents of some manganese nodules

Nodule description	Uranium concentration (p.p.m.)
Horizon nodule, from 40°14′ N and 155°15′ W at a depth of 5500 m.	3·9, 3·6, 3·6
Nodule from Downwind Core DWBG47 taken at 36°33′ S and 137°24′ W at a depth of 4700 m.	4·6
Nodule from Downwind Core DWBG52 taken at 40°36′ S and 132°49′ W at a depth of 5120 m.	3·6
Nodule from Downwind Dredge DWHD taken at 37°04′ S and 81°50′ W collected from a depth of 4000 m.	4·0
Nodule from Lamont Theta Trawl no. 4 taken at 29°18′ N and 57°20′ W at a depth of 5400 m.	5·0

useful over the time period of zero to a half million years (Fig. 1). Two prerequisites primarily govern the application of U–Io dating to minerals: first of all, there can be no alterations to the mineral which would result in the addition or removal of uranium, ionium or the intermediate radionuclides in this naturally occurring radioactive series; and secondly, there can be no unsupported ionium initially present in the sample. A ready test of the second qualification may be found in the presence of any thorium, if it is assumed that any unsupported ionium would come from the sea-water. The deduced ratio of ionium to thorium (in units of disintegration per time interval) in sea-water can be of the order of 35 (Goldberg and Koide, 1958). Hence, any significant amounts of thorium in such samples would negate any derived age.

Table 3 presents thorium, in units of parts per million by weight, and ionium, in equivalents of uranium, concentrations in some oolites and corals. These thorium isotopes were assayed radiometrically by a previously described technique (Goldberg and Koide, 1958). Five of the seven samples were free of thorium within the limits of error, while the oolites from Laguna Madre and from the Great Salt Lake had thorium contents of about 1 p.p.m. and are undatable by this technique (see below). Two of the samples from Bahama Bank gave zero age, reasonable numbers inasmuch as the samples came from the surface of the sedimentary deposits. The remaining samples, including two corals, show a spectrum of ages from 9000–260,000 years. These results, although not forming a part of a geologic problem, are not in conflict with known geologic evidence (R. N. Ginsburg, personal communication). An estimate of the lower limit of age detection and the influence of thorium isotopes, accumulated from sea-water by the calcium carbonate, on the results can be ascertained in the following ways. For a 2 g sample, in which the thorium isotopes are recovered with a 100 per cent efficiency, 60 net counts over background are detectable in a 600 min counting period in our instrumentation. This is equivalent to 0·2 disintegrations per min, correcting for our geometry of 52 per cent. Assuming 3 p.p.m. of uranium in the sample, the ratio of activity of ionium to uranium is 0·05 which results in a minimum age of detection of around 6000 years. Larger samples, obviously, would

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reduce this figure and there is no experimental reason to prohibit processing samples in the hundreds of grammes.

A thorium contamination of 0·05 μg, in a 2 g sample, represents an ionium equivalent of 0·3 μg of uranium, assuming an ionium–thorium activity ratio of 35. This thorium value represents about the lower limit of detectability and an error in the age of 6000 years. However, 2·0 μg of thorium in a 2 g sample gives spurious ages of tens of thousands of years.

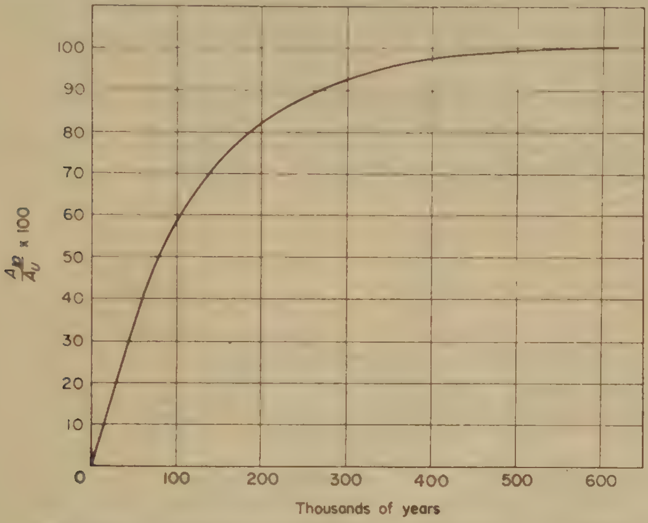

Fig. 1. The growth of ionium from its parent uranium as a function of age.

The uranium concentrations in the ferromanganese minerals (Table 5) are of the order of 4–5 p.p.m. and are markedly lower than the corresponding thorium concentrations of 30–100 p.p.m. (GOLDBERG and PICCIOTTO, 1955). Assuming that these minerals obtain their constituents from the dissolved chemical species in sea-water, there is a marked fractionation against uranium compared to thorium, for the uranium content of sea-water is of the order of several parts per billion whereas the thorium is less than five-hundredths of a part per billion. This situation probably arises from the fact that the thorium is in solution in the tetravalent state while the uranium is in the hexavalent state, possibly complexed with carbonate as the uranyl ion (STARIK and KOLYADIN, 1957).

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REFERENCES

BARNES J. W., LANG E. J. and POTRATZ H. A. (1956) Ratio of ionium to uranium in coral limestone. *Science* **124,** 175–176.

GOLDBERG E. D. and PICCIOTTO E. (1955) Thorium determinations in manganese nodules. *Science* **121**, 613–614.

GOLDBERG E. D. and KOIDE M. (1958) Ionium–thorium in deep-sea sediments of the Pacific. *Science* **128**, 175–176.

FISHER S. and KUNIN R. (1957) Use of ion exchange resins for determination of uranium in ores and solutions. *Analyt. Chem.* **29**, 400–402.

LOWENSTAM H. A. and EPSTEIN S. (1957) On the origin of sedimentary aragonite needles of the Great Bahama Bank. *J. Geol.* **65**, 364–375.

REVELLE R. and FAIRBRIDGE R. (1957) Carbonates and carbon dioxide. *Treatise on Marine Ecology and Paleoecology* Vol. 1, pp. 239-96. Memoir 67, Geological Society of America.

SACKETT W. (1958) Thesis, University of Washington, St. Louis, Mo.

STARIK I. E. and KOLYADIN L. B. (1957) The conditions of occurrence of uranium in sea-water. *Geochymia* 204–13.

THOMPSON T. G. and CHOW T. J. (1955) The strontium/calcium atom ratio in carbonate-secreting marine organisms. *Deep-Sea Res.* Suppl. **3**, 20–39.

YOE J. H., WILL F. and BLACK R. A. (1953) Colorimetric determination of uranium with dibenzoylmethane. *Analyt. Chem.* **25**, 1200–1204.

(978)

COSMIC-RAY-PRODUCED Si^{32} IN NATURE

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(Received September 21, 1959)

The radio-isotope Si^{32}, expected to be produced in the nuclear spallations of atmospheric argon by cosmic rays, has been detected in the marine environment. Its half-life, which is as yet only known approximately as 700 years,[1] lies between those of two cosmic-ray-produced isotopes, C^{14} (5570 years) and H^3 (12.5 years). This isotope, therefore, bridges the gap in time periods which can be adequately studied by the latter nuclides. The potential significance of Si^{32} in the studies of geophysical and geochemical processes such as circulation and mixing within the oceans, and chronology of rapidly accumulating siliceous marine sediments, ice caps, etc., will be discussed elsewhere.

The production rate of Si^{32} has been calculated on the basis of the existing cosmic-ray data and the observed fall-out of another cosmic-ray-produced isotope, P^{32} arising from spallation of atmospheric argon. The global production rate thus obtained is 2.0×10^{-4} Si^{32} atoms/cm^2 sec. The corresponding inventory of Si^{32} on the earth is 28 kilocuries or 1.75 kg.

The principal exchange reservoir for Si^{32} is the marine hydrosphere, which probably receives most of its activity via the oceanic rains. Using its calculated production rate and the known concentration of silicon in oceanic waters, we estimate that approximately 100 and 40 tons of surface and deep waters, respectively, are required to yield an activity of one disintegration per minute. Sponges which lay down an opaline (silicon dioxide) skeleton derived from the silica in marine waters provide a truly natural means of concentration.

Approximately 200 grams of silicon dioxide were obtained after thorough cleansing of three inshore sponges dredged from the Gulf of California in 1956. The activity of Si^{32} was measured by counting the activity of its daughter nuclide P^{32} by milking after a period of three months. The results, to be described in detail elsewhere, conclusively proved that the observed activity was due to P^{32} produced in the decay of its parent nuclide Si^{32}.

The observed activity of 19.6 disintegrations/minute per kg Si is consistent with that calculated on the basis of the estimated production rate of Si^{32} and a mean mixing time of 2000 years between the deep and surface oceanic waters.

This work was supported by grants from the Atomic Energy Commission, Division of Biology and Medicine, and the Air Force Geophysics Research Directorate.

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[1] M. Lindner, Phys. Rev. 91, 642 (1953).

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MINOR LINEATIONS IN THE PACIFIC BASIN

BY H. W. MENARD

Widely distributed minor lineations in the Pacific Basin lie in a pinnate pattern relative to the major lineations such as island arcs, archipelagoes, and fracture zones. Individual minor lineations generally are 20–200 km long and consist of: (1) elongate submarine volcanoes, atolls on volcanic platforms, and volcanic islands; (2) lines of closely spaced circular submarine volcanoes; (3) asymmetrical ridges; (4) narrow troughs ordinarily associated with parallel asymmetrical ridges; (5) straight troughs resembling submarine canyons on continental and insular slopes.

Compared to faults on land these "minor" lineations are rather large features, but at sea the most detailed techniques of location and very closely spaced sounding lines are required to survey most of them. Within a few hundred miles of land, electronic positioning is possible. Farther out to sea, buoys are planted, or an intricate pattern of dead reckoning may be used. The requirement of accurate positioning is no more critical than accurate sounding with recording, high-performance echo sounders. For this reason the large network of random spot soundings in the Pacific is of little use in detecting minor lineations. Narrow troughs are particularly elusive because the steep sides all but disappear on the record, and it may appear that little change in depth has occurred on the phased type of recorder used by oceanographers. Almost 200 minor lineations are known in the Pacific Basin at present. Inasmuch as all of them are in specially surveyed areas which amount to only a small fraction of the basin area, it may be anticipated that thousands remain to be found.

Elongate volcanoes are the most common minor lineations in the Pacific Basin. Excellent examples are San Juan Seamount (Shepard and Emery, 1941, Pl. 4), San Benedicto Island in the Revillagigedo Group (Richards, 1957, Theses, Univ. Calif. at La Jolla, Pl. 2A), and Takaroa Atoll in the Tuamotu Archipelago. Individual elongate volcanoes grade into circular volcanoes which are so closely spaced that they have a common base. Clipperton Island and the adjacent seamounts are an example (Menard and Fisher, 1958, Fig. 3). These in turn grade into closely spaced circular seamounts which are not connected topographically, such as the group associated with Fieberling Guyot (Menard, 1955b, Pl. 1; H.O. Chart 0527).

Small asymmetrical ridges normally are associated with deep troughs, but the ridges around Hawaii are not, nor is one south of the Murray fracture zone. Narrow troughs with parallel asymmetrical ridges on one or both sides have been described both north and south of the Clipperton fracture zone (Menard and Fisher, 1958, p. 249), and others occur in the vicinity of the Clarion, Murray, and Mendocino fracture zones and also south of the Pioneer Ridge which lies parallel to and south of the Mendocino fracture zone.

Straight troughs, attributed to faulting, have been described on the continental sides of the Kurile Trench (Udincev, 1955, Pl. 3) and the Aleutian Trench (Gates and Gibson, 1956, Fig. 3). These troughs superficially resemble normal submarine canyons, but they are straight, have parallel trends, and in both areas they have about the same oblique trend to the trench axis, so that they appear to be fault troughs.

Two patterns of minor lineations are identified, a pinnate pattern centered on major lineations, and a less definite herringbone pattern extending across crustal blocks and changing direction at the fracture zones in the northeastern Pacific. In addition, both major and minor lineations have a relatively constant trend in very large areas near the continental margins of North American and South America.

The pinnate pattern consists of minor lineations on both sides of major lineations with different but relatively constant trends on each side (Fig. 1). The whole pattern resembles a feather with the major lineations as the shaft and the minor lineations as barbs. The angle between representative minor lineations, measured as the "V" of the barbs, ranges from 66° to 140° and commonly is not bisected by the major lineation. Separated into classes according to associated types of major lineation, the angles are either about 70° or 90° for fracture zones, 105°–110° for linear archipelagoes, and about 140° for the Kurile Trench. Although the grouping in classes is suggestive, the sample is

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not large enough to assure that significant differences in angles exist in the several types of major lineations.

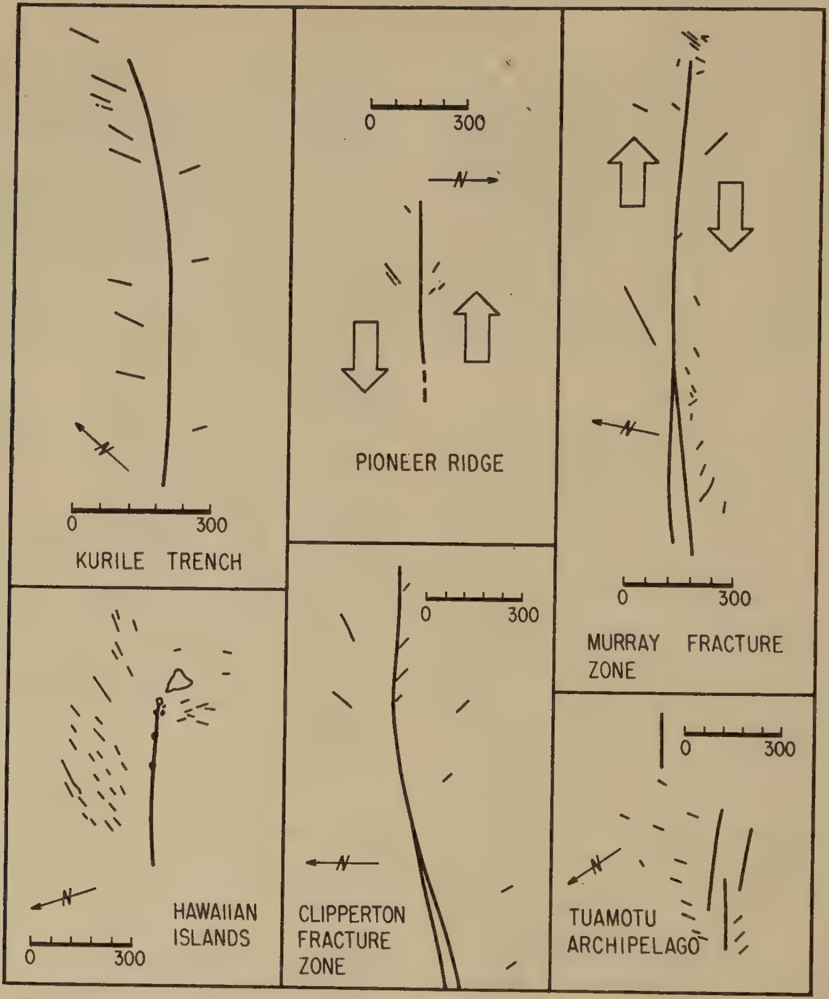

Figure 1.—Pinnate Pattern of Minor Lineations Around Major Lineations
Scale in nautical miles

An exception to the general rule of constant trend of minor lineations on one side of a major lineation exists south of the Murray fracture zone (Fig. 1) in the Moonless Mountain region (Menard, 1955a, p. 37). These mountains consist of 15 known volcanoes ranging in height to 3500 m, and almost all are markedly linear. (The more nearly circular peaks are not plotted on Figure 1.) The lineations of the peaks which have been surveyed in most detail lie in two groups, one trending northwesterly and the other northeasterly. In most other regions, however, the minor lineations are as uniform in trend as any group of continental faults distributed over a similar area. The lineations northeast of the Hawaiian Islands and those south of Clipperton fracture zone (Fig. 1), for example, have as constant a trend and are spread over about the same area as the faults of the Basin and Range Province in the United States.

The herringbone pattern of minor fractures incorporates the pinnate patterns around different fracture zones into a single whole. This arises from the fact that the "V's" in the pinnate patterns of adjacent fracture zones point in opposite directions (Fig. 2). Since most of the minor lineations in the northeastern Pacific fit into both the herringbone and pinnate patterns the two names, in a sense, merely indicate emphasis, the former on minor lineations within crustal blocks and the latter on minor lineations at the margins of blocks. However, there are some lineations in the middle of crustal blocks, suggesting that the herringbone pattern is more significant although it is not so definite as the pinnate one. Among the mid-block lineations, the best established are in the Baja California Seamount Province between the Murray and Clarion fracture zones where at least two ranges of seamounts have the northwesterly trend found at the margins. The ranges have not been surveyed, but closely spaced random sounding lines by various Scripps expeditions indicate lines of closely spaced small seamounts. A similar range of small seamounts between the Murray fracture zone and the Pioneer Ridge trends northeasterly across almost half the width of the crustal block and has the same trend as the fractures at the margins of the block.

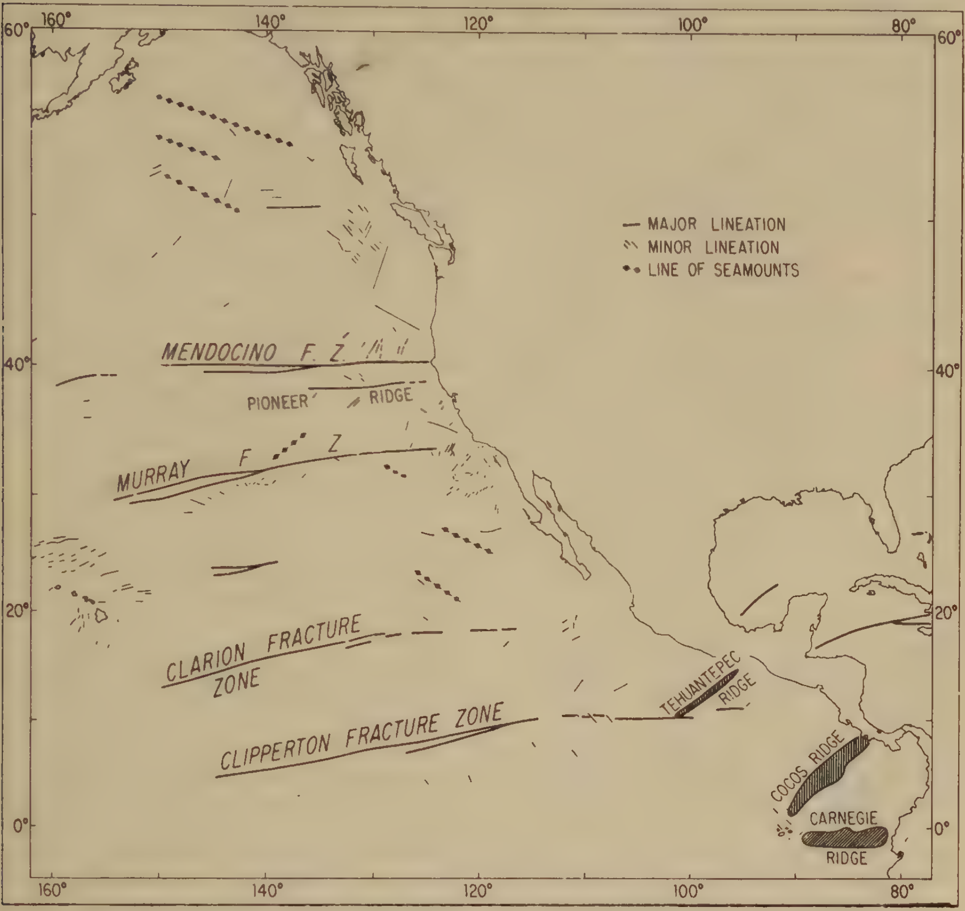
60°
160°
140°
120°
100°
80°
40°
20°
0°
— MAJOR LINEATION
MINOR LINEATION
LINE OF SEAMOUNTS
MENDOCINO F. Z.
PIONEER RIDGE
MURRAY F. Z.
CLARION FRACTURE ZONE
CLIPPERTON FRACTURE ZONE
TEHUANTEPEC RIDGE
COCOS RIDGE
CARNEGIE RIDGE

Figure 2.—Major and Minor Lineations in the Northeastern Pacific Basin

The relatively constant trend of minor lineations between fracture zones forms a herringbone pattern in this part of the basin. Off Central America, Mexico, and California, most lineations are northeasterly.

A prominent northeasterly trend exists on the deep-sea floor in a band extending from northern California to northern Chile. In the less densely sounded southern region the trend comprises three great submarine ridges, the Tehuantepec Ridge (Menard and Fisher, 1958, Fig. 1), the Cocos Ridge (Shumway, 1954, Fig. 2), and the Nasca Ridge which was surveyed during the Downwind Expedition. All the ridges are connected with, and appear to branch from, fracture zones with easterly trends. Off Baja California and California, the northeasterly trend is exhibited by at least 20 large volcanoes including some on the continental slope and borderland (Shepard and Emery, 1941, p. 33–34). The northeasterly lineations have not been found north of Pt. Arena in California where the San Andreas fault trends out to sea. A much less prominent northerly trend of minor lineations also exists off Baja California. This trend includes the active volcano of San Benedicto Island, the undissected volcanoes of Guadalupe Island, and a few small seamounts. Inasmuch as none of the volcanoes with northeasterly trends is active, these with northerly trends may be younger.

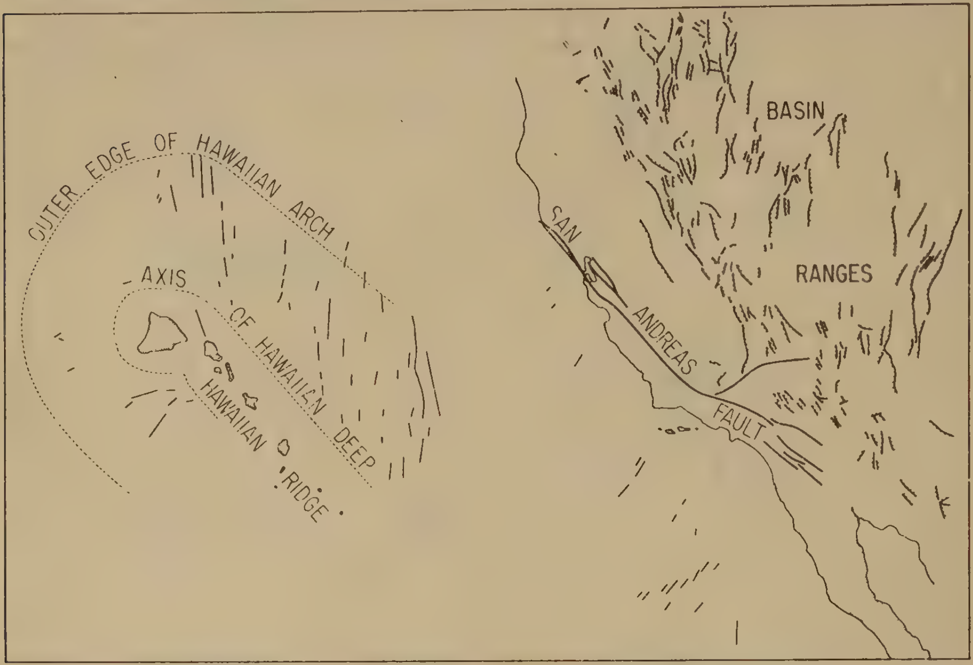

Figure 3.—Comparison of the Scale of Major and Minor Lineations around the Hawaiian Islands (mirror image) with the San Andreas Fault and the Basin Ranges

A well-developed group of lineations off Vancouver trends northwesterly. Individual lineations are parallel to and lie in the area between the active seismic lines northwest of Cape Mendocino and southwest of Queen Charlotte Island (Gutenberg and Richter, 1954, p. 34). The group also lies southeast of an east–west ridge which has been traced for 350 km (Robert Hurley, personal communication, 1959) and which may be another of the fracture zones of the northeastern Pacific.

Minor lineations consisting of elongate volcanoes, lines of volcanoes, asymmetrical ridges, and narrow troughs mark tension faults. The origin of the tension, however, need not be uniform. The en echelon pattern of a group of very elongate volcanoes off Baja California suggests tension cracks produced by an underlying shear. The minor lineations around the Hawaiian Islands in general lie on the Hawaiian Arch (Dietz and Menard, 1953, Fig. 3; Hamilton, 1957, Fig. 4), and they may be formed by keystone faulting incidental to the uplift of the arch. Likewise, most troughs have asymmetrical ridges on each side and conceivably might result from keystone faulting on anticlines. However, volcanoes, asymmetrical ridges, and troughs all have the same orientation in some regions, and it is difficult to believe that they do not have a common origin.

The oceanic crust of the eastern Pacific is fractured into blocks with dimensions of the order of 10^5–10^6 km^2. Major easterly lineations called fracture zones (Menard, 1955b) exist at the margins of the blocks, and large displacements have taken place on some of, if not all, the fracture zones. Right-lateral faulting of about 150 km has been measured on the Murray fracture zone (Mason, 1958, p. 328; Menard and Vacquier, 1958, p. 2–5), and left-lateral faulting of 250 km on the Pioneer Ridge (Victor Vacquier, personal communication, 1959). Pinnate minor lineations border the two fracture zones where displacement has been measured (Fig. 1). A similar pattern of minor lineations is associated with many other major lineations in the Pacific Basin. If the major and minor lineations could be related to a common origin, it would suggest that horizontal displacement has occurred on all the major lineations.

The herringbone pattern is not definite enough at present to justify elaborate speculations about origin. The strain pattern seems to be constant within a crustal block and differs systematically from block to block, but even these conclusions need confirmation from further mapping.

The scale of the crustal distortion implied by the common association of patterns of minor lineations with major lineations merits attention. If a mirror image of the Hawaiian Islands lineation is compared with the San Andreas fault (Fig. 3), the minor lineations associated with the Hawaiian lineation lie in the same area as the Basin Ranges and have about the same trends, spacing, and lengths as individual ranges. All these similarities may be attributed to coincidence, but the scale is significant. Horizontal displacement along the San Andreas fault of the magnitude suggested by Hill and Dibblee (1953, p. 445–449) implies major crustal shortening and stretching somewhere. The distribution of major and minor lineations on the sea floor suggests that geologists may justifiably look far afield for the secondary effects of large-scale wrench faulting.

References Cited

Dietz, R. S., and Menard, H. W., 1953, Hawaiian Swell, Arch, and Deep, and subsidence of the Hawaiian Islands: Jour. Geology, v. 61, p. 99–113

Gates, O., and Gibson, W., 1956, Interpretation of the configuration of the Aleutian Ridge: Geol. Soc. America Bull., v. 67, p. 127–146

Gutenberg, B., and Richter, C. F., 1954, Seismicity of the earth: Princeton, N. J., Princeton Univ. Press, 310 p.

Hamilton, E. L., 1957, Marine geology of the southern Hawaiian Ridge: Geol. Soc. America Bull., v. 68, p. 1011–1026

Hill, M. L., and Dibblee, T. W. Jr., 1953, San Andreas, Garlock, and Big Pine faults, California: Geol. Soc. America Bull., v. 64, p. 443–458

Mason, R. G., 1958, A magnetic survey off the coast of the United States between latitudes 32° and 36° N. and longitudes 121° and 128° W.: Geophys. Jour., v. 1, p. 320–329

Menard, H. W., 1955a, Fractures in the Pacific floor: Sci. Am., v. 193, p. 36–41

—— 1955b, Deformation of the northeastern Pacific Basin and the west coast of North America: Geol. Soc. America Bull., v. 66, p. 1149–1198

—— In press, Possible pre-Pleistocene deep-sea fans off central California: Geol. Soc. America Bull.

Menard, H. W., and Fisher, R. L., 1958, Clipperton fracture zone in the Northeastern Equatorial Pacific: Jour. Geology, v. 66, p. 239–253

Menard, H. W., and Vacquier, V., 1958, Magnetic survey of part of the deep-sea floor off the coast of California: Office of Naval Research, Research Reviews, June, p. 1–5

Shepard, F. P., and Emery, K. O., 1941, Submarine topography off the Calitornia Coast: Geol. Soc. America Special Paper 31, 171 p.

Shumway, G. A., 1954, Carnegie Ridge and Cocos Ridge in the eastern equatorial Pacific: Jour. Geology, v. 62, p. 573–586

Udincev, G. B., 1955, Geological structure of the Kurile-Kamchatka Trough: Priroda, v. 12, 79–82, Defence Res. Board, Canada, T 217 R, by E. R. Hope

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(985)

DISTRIBUTION ET ORIGINE DES ZONES PLATES ABYSSALES (1)

Henry W. MENARD (2)

SUMMARY

Three classes of topography of low relief may be distinguished in the Pacific : (1) a very widespread and characteristic hilly terrane, (2) smooth abyssal plains off the continent in the northeastern Pacific, and (3) smooth archipelagic aprons around the island groups of the western and southern Pacific. Similar topography exists in other oceans. The smooth areas apparently are formed by burial of a pre-existing hilly terrane. Sediment derived from continents and apparently spread by turbidity currents is the dominant material that smooths abyssal plains. Volume-wise, lava flows appear to be dominant in forming archipelagic aprons, but sediment is required to perfect the smoothing. Preliminary estimates suggest that the total areas of abyssal plains and archipelagic aprons in the world are roughly equal. The total area of known smooth deep sea floor in the Pacific is greater than in the Atlantic because of the contribution of archipelagic aprons. However, the proportion of the Atlantic sea floor (below 4 000 m) that is smooth is greater than the Pacific. Smoothing by settling out of pelagic material is comparatively unimportant.

Introduction

PROBLÈME.

Environ 80 à 85 % du relief des profondeurs connues du Pacifique sont formés par une succession de collines ayant une hauteur moyenne de 300 mètres. Ailleurs, le fond est relativement plat et a la forme de cônes d'alluvions *(fans)*, de supports d'archipels se recouvrant, et de plaines. Les régions plates des fonds océaniques sont apparemment produites par le comblement de zones accidentées, mais on discute de la cause de ce comblement. Les deux hypothèses en présence sont les dépôts de lave, et les dépôts laissés par les courants de turbidité. Cet article essaye de montrer que les deux phénomènes peuvent entrer en jeu, et essaye aussi d'estimer leur importance relative comme agents de comblement.

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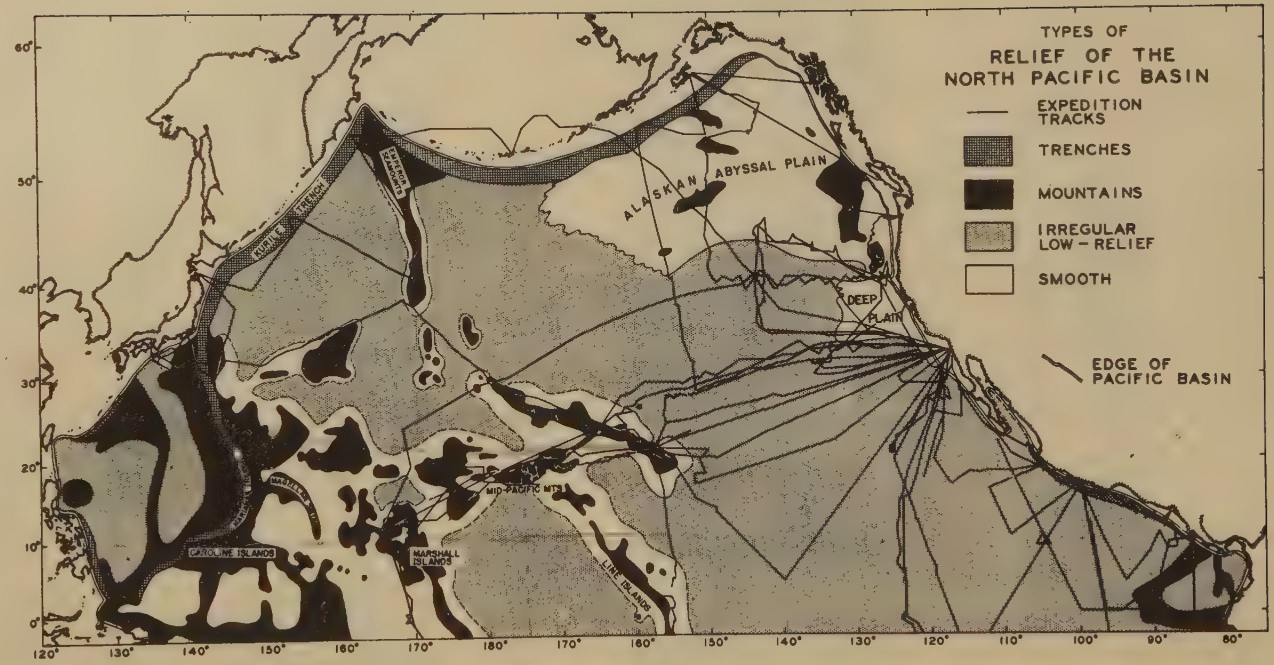
TYPES OF
RELIEF OF THE
NORTH PACIFIC BASIN
EXPEDITION TRACKS
TRENCHES
MOUNTAINS
IRREGULAR LOW-RELIEF
SMOOTH
EDGE OF PACIFIC BASIN
ALASKAN ABYSSAL PLAIN
DEEP PLAIN
EMPEROR SEAMOUNTS
KURILE TRENCH
MID-PACIFIC MTS
MARSHALL ISLANDS
CAROLINE ISLANDS
LINE ISLANDS
60°
50°
40°
30°
20°
10°
0°
120°
130°
140°
150°
160°
170°
180°
170°
160°
150°
140°
130°
120°
110°
100°
90°
80°

Fig. I
Répartition des divers types de topographie dans le Bassin Nord Pacifique.

SOURCES DE RENSEIGNEMENTS NON PUBLIÉS.

Les lignes de sondages de la Scripps Institution of Oceanography et des laboratoires électroniques de la Marine s'étendent sur plus de 300.000 km de long et forment maintenant un réseau couvrant la plus grande partie du Bassin du Pacifique (Fig. 1). On a plus de 5,5 kilomètres de bande d'enregistrement sur lesquelles 3,5 kilomètres proviennent d'un sondeur Edo (AN/UQN 1-b) modifié de façon à ce qu'il enregistre à une échelle convenable, quelle que soit la profondeur. La plupart des enregistrements sont faits à une fréquence constante. L'échelle de ce type d'enregistrement est telle que 100 mètres de dénivellation correspondent à 1,9 cm de papier, et les profondeurs peuvent être lues à ± 1 m près, quelle que soit la profondeur. Cependant on n'a jamais essayé d'attribuer un sens à de telles lectures.

D'autres informations non publiées ont aussi été utilisées pour étudier les faibles reliefs du Pacifique. Dans le golfe de l'Alaska et les eaux voisines, et au voisinage des îles Hawaï, ce sont des lignes de sondes du Coast and Geodetic Survey qui sont les principales sources de renseignements concernant la bathymétrie. Partout ailleurs, les sondages de la Marine Américaine sont très utiles. Les enregistrements au voisinage des îles de l'Equateur proviennent du bateau de recherches « *Charles H. Gilbert* » du Fish and wildlife Service, et ont été dépouillés par le Dr William F. ROYCE.

Faibles reliefs du Bassin du Pacifique

DÉFINITIONS.

Les faibles reliefs sont les reliefs à petite échelle, en opposition avec les montagnes sous-marines, les fosses et les grandes surélévations comme la remontée des Hawaï. Ils comportent les reliefs plats, comme les plaines, mais la plupart des faibles reliefs sont accidentés et sont formés par une succession de collines à flancs plus ou moins raides, des vallées, des seuils, et des fosses ayant un relief maximum inférieur à 1 km. Dans tout le Pacifique, la hauteur moyenne des faibles reliefs, d'après les échogrammes, est de 300 mètres sur une distance de 200 km. La hauteur maximum, dans certaines régions n'est que de 60 mètres, et ailleurs elle peut être de 550 mètres pour 200 km. Presque tous ces reliefs semblent se trouver au-dessus du niveau général du fond de l'Océan. Les fosses ou bassins au-dessous du niveau général sont rares.

Le fond plat a une pente de seulement quelques unités pour mille, sauf près du sommet d'un grand tablier concave vers le haut où elle peut atteindre 0,02 (2 %). Les fonds plats comprennent les plaines abyssales et, en beaucoup d'endroits, la « remontée » continentale *(continental rise)*, les cônes et les supports d'archipels. La plus grande partie du relief local de ces régions plates consiste en chenaux de mer profonde, bordés par endroits de levées de terrain. Quelques sommets de collines ou de montagnes partiellement enterrées s'élèvent abruptement de ce qui sans cela serait des fonds plats.

Une plaine abyssale est une zone du fond de l'océan dans laquelle le fond est plat et la pente de ce fond est inférieure à 1/1.000 (HEEZEN, EWING et ERICSON, 1954). L'auteur ajouterait la restriction suivante : les plaines abyssales sont adjacentes à une zone continentale.

Un support d'archipel (archipelagic apron) est l'anneau de fond marin plat qui entoure la plupart des îles et les anciens groupes d'îles du Pacifique, et est lui-même entouré par des zones étendues ayant un relief normal de collines (Fig. 1). Le bord le plus éloigné d'un support peut avoir une faible pente, comparable à celle d'une plaine abyssale; une coupe à travers toute sa largeur est concave vers le haut.

Distribution géographique

Les surfaces plates des fonds abyssaux dans le Pacifique sont nettement réparties en deux groupes : les plaines abyssales du Pacifique Nord-Est et les supports d'archipels dans le Pacifique Ouest et Sud. La seule exception connue à cette répartition est le petit cône sous-marin au Sud de Honshu dans le Pacifique Ouest.

On appelle dans cet article, plaine abyssale de l'Alaska, la plaine abyssale qui se trouve au Sud-Ouest au large de la partie Sud de l'Alaska. Le fond sous-marin a presque partout une pente douce et graduelle en partant de la pente continentale, traversant un groupe de cônes d'alluvions et allant vers la plaine abyssale. Dans la région des montagnes sous-marines du Golfe d'Alaska, cette pente douce est coupée par au moins 36 grandes montagnes (Menard et Dietz, 1951) mais elle ne perd pas ses caractéristiques de plaine. La plaine est limitée au Nord par la remontée vers le large de la fosse Aléoutienne, et au Sud par les hauteurs asymétriques qui forment la partie Nord de la zone de failles de Mendocino (Menard, 1955*b*). La frontière ouest n'est pas connue car on manque de sondages dans cette région. Cependant, un certain nombre de lignes de sonde du Coast and Geodetic Survey montre que la plaine s'étend au moins sur 2.200 km au large de la pente continentale. Dans sa partie connue le plus vers le large, les zones de collines sont plus grandes et plus fréquentes que plus près des côtes, ce qui suggère que le bord réel le plus vers le large de cette plaine n'est pas très loin. Toutefois, ces collines peuvent n'être que des interruptions locales de la plaine abyssale de l'Alaska qui peut s'étendre jusqu'au centre du bassin Nord Pacifique. On ne connait aucune barrière topographique importante dans cette région. La plaine abyssale de l'Alaska a une surface minimum de 3.400.000 kilomètres carrés et est la plus grande zone plate connue dans les océans (Tableau I).

La Plaine Profonde du Pacifique Nord, au large de la Californie centrale, est une des plus petites régions plates qu'on connaisse, elle a une superficie d'environ 570.000 kilomètres carrés. Les grands canyons sous-marins de la Californie Centrale (Shepard et Emery, 1951) vont en descendant vers des chenaux et des cônes profonds bien développés (Menard, 1955*a*) et les cônes descendent graduellement dans la plaine abyssale avec une pente d'environ 0,01 vers l'Ouest-Sud-Ouest. L'extrémité la plus éloignée de la plaine se trouve à environ 700 km de la côte. Plus loin vers l'Ouest, le fond de la mer est accidenté mais continue à descendre pendant au moins 900 km. Par conséquent, la Plaine Profonde n'est pas un dépôt sédimentaire situé dans la partie la plus basse d'un bassin, mais est accrochée au sommet d'une longue pente, comme un cône alluvial au rebord d'un bassin désertique en pente. Comme la plaine abyssale qui se trouve au Sud de Terre-Neuve (Heezen, Ewing et Ericson, 1954) elle ne semble se développer qu'en se surélevant.

Le cône de mer profonde au Sud de Honshu a été découvert, et recoupé en deux endroits, par Baird au cours de l'expédition transpacifique. Juste au Sud de Fuji Yama se trouve Suruga Wan, dont le fond forme une cuvette (Shepard, 1948) qui, traversant la pente continentale, conduit aux cônes de grande profondeur. Un glisse-

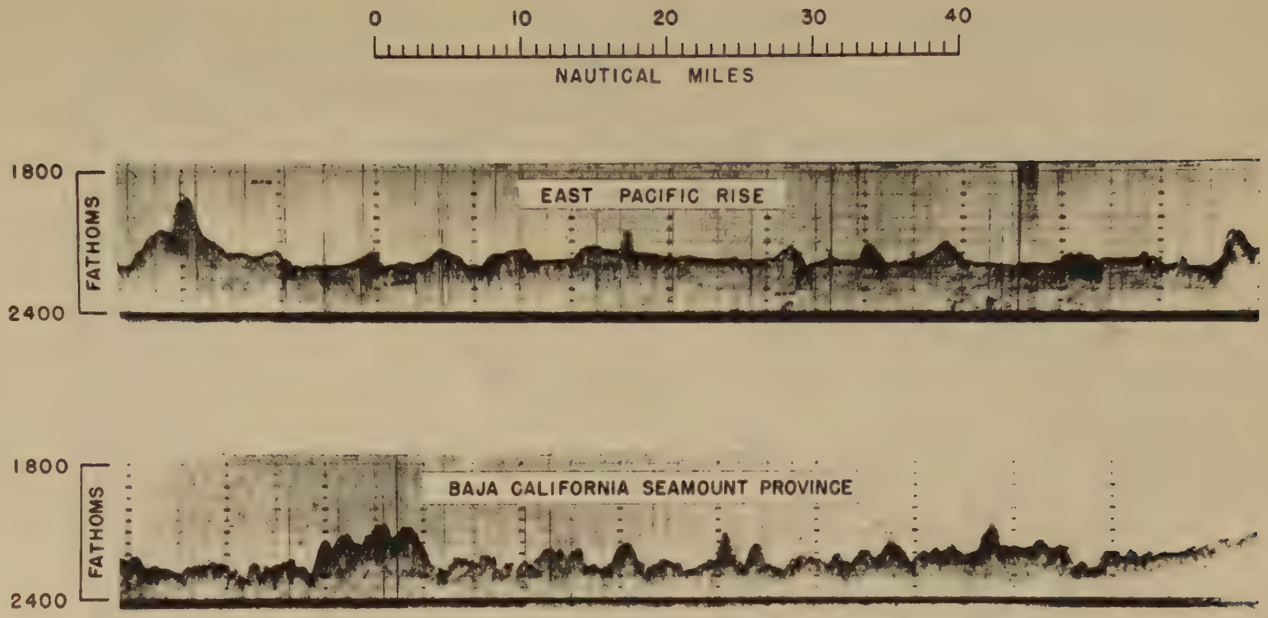

Fig. II

Bande de sondages de terrains accidentés en collines suggérant l'effet d'adoucissement de la sédimentation pélagique dans la Remontée (Rise) du Pacifique Est.

ment sous-marin dans cette cuvette est indiqué par les changements de profondeur (Shepard, 1933) et il n'y a besoin que d'un courant de turbidité pour transporter ce glissement d'eaux peu profondes à plus de 300 km vers le bas dans la cuvette et au-delà du cône.

Les supports d'archipels sont les régions plates qui entourent les groupes d'îles et les anciens groupes d'îles du Pacifique Ouest (Menard, 1956). Les supports bordent tous les archipels qu'on a sondés dans le Pacifique Ouest, les îles Cook, Ellis, Gilbert, Hawaï, de l'équateur, Marquises, Marshall, Samoa, de la Société et Tuamotou. Ils bordent aussi tous les groupes d'anciennes îles immergées (guyots) qu'on a sondés dans le Pacifique Ouest : les montagnes sous-marines de l'Empereur, de Magellan et les montagnes centrales du Pacifique. Dans des zones entourées de groupes d'îles, les supports peuvent se transformer en grandes plaines, telles que celle qui se trouve entre les îles Caroline et Gilbert.

Les supports d'archipels ressemblent à la topographie sous-marine la plus courante autour des continents en ce sens que les cônes de mer profonde bordent les pentes des îles, et, à leur tour, sont entourés de plaines presque complètement plates. Les supports, au moins en certains endroits, sont entourés par un anneau de petites surélévations qui agissent comme une digue et empêchent les coulées de lave de s'étendre et gênent les courants de turbidité. Cette retenue derrière la digue produirait les pentes très douces qui se trouvent à l'extrémité la plus éloignée des supports d'archipels.

A part les plaines abyssales plates et les supports d'archipels, le relief profond du bassin du Pacifique est accidenté mais pas uniformément. Le réseau de sondages à grande échelle du Pacifique convient parfaitement pour montrer qu'il existe des différences régionales, mais dans la plupart des régions, il est trop peu serré pour permettre des comparaisons quantitatives ayant un sens. Toutefois, quelques régions

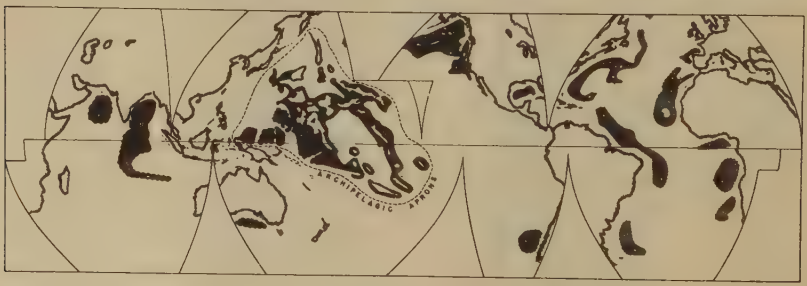

Fig. III

Répartition de zones connues et de quelques zones hypothétiques à relief adouci. Les limites indiquées en lignes ondulées sont assez peu précises. Les zones complètement entourées par des lignes ondulées peuvent être des zones à relief adouci mais on ne possède pas de bandes de sondages qui donnent une preuve de leur existence. Les flèches indiquent les directions générales des pentes du fond sous-marin. D'après Browne (1954), Dietz (1953), Ewing et al. (1953, Ewing et al. (1955), Gaskell et Swallow (1953), Heezen, Ewing et Miller (1953), Heezen, Ewing et Ericson (1954), Koczy 1954), Menard (1955*a*), Menard (1956) et les cartes du Bureau hydrographique et du Service hydrographique de la Marine américaine.

peuvent être rangées par ordre de rugosité croissante : 1) La région entre les montagnes sous-marines de l'Empereur et la ligne des fosses du Japon et de Kurile est légèrement ondulée et relativement plate en certains endroits. Cependant le relief est trop important, et même le petit relief est trop marqué pour que ce soit une plaine abyssale. 2) La zone de la barrière du Pacifique Est, au Sud de l'Equateur comprend des collines, mais les collines et les bassins sont arrondis et atténués comme par une couche de sédiments. De nombreux petits bassins ont des fonds plats (Fig. 2 et 3). La province des montagnes sous-marines de Baja California, province située entre les îles Hawaï et Baja California, a de nombreuses collines sur toute sa surface, sans qu'il soit question d'un adoucissement du relief sur une surface de plus de 3.000.000 kilomètres carrés (Fig. 2).

Origine des zones plates

On peut distinguer dans le Pacifique trois sortes de faibles reliefs : 1) zones de collines; 2) plaines abyssales — zones plates bordant les continents et 3) les supports d'archipels — zones plates bordant les groupes d'îles ou les guyots (Fig. 1). Les zones plates, dans toutes les parties des océans qui ont été étudiées en détail, semblent avoir été créées par recouvrement de zones accidentées (Heezen, Ewing et Ericson, 1954; Browne, 1954; Menard, 1955; Menard, 1956). Par conséquent, le problème de l'origine d'une zone plate se réduit à identifier l'agent de recouvrement. Les seules possibilités sont la sédimentation à partir d'une suspension, la sédimentation par courant de turbidité, et les coulées de lave. Les plaines abyssales et les supports d'archipels se ressemblent en beaucoup de points, spécialement dans leur aplanissement, mais les différents agents de recouvrement peuvent avoir un degré d'importance différent dans leur production.

Plaines abyssales

Les caractéristiques permettant la mise en évidence d'un recouvrement sont les suivantes :

1. Les carottages montrent que, au moins le sommet (de 3 à 10 mètres) du matériau de recouvrement est sédimentaire (Nord Atlantique, Ericson, Ewing et Heezen, 1952; Sud Atlantique, Phleger, Parker et Peirson, 1953; Nord-Est Pacifique, Revelle et al., 1955).

2. Les mesures de réflexion et de réfraction seismiques montrent qu'il y a 1 à 2 km d'épaisseur de sédiments au-dessous des plaines abyssales et même plus au-dessous de la remontée continentale *(continental rise)* (Nord Atlantique, Ewing, Sutton et Officer, 1954; Océan Indien, Gaskell et Swallow, 1953).

3*a*. Des sables grossiers, des argiles et des matériaux biogènes transportés sont courants dans les échantillons provenant des plaines abyssales, mais des sédiments pélagiques recouvrent les petites collines qui s'élèvent dans les plaines et autour des plaines. La distribution des sédiments montre qu'ils ont été déposés plutôt par des courants de turbidité se déplaçant sur le fond que par des chutes de matériau en suspension dans l'océan (Atlantique, Ericson et al., 1955).

3*b*. L'existence de chenaux et de cônes profonds, la pente des plaines autour des chaînes et des montagnes sous-marines, et la répartition des bassins dans des endroits protégés des courants du fond par des barrières confirment que les courants de turbidité sont les principaux agents de la sédimentation (Nord Atlantique, **Heezen**, **Ewing** et **Ericson**, 1954; Pacifique Nord-Est, **Menard**, 1955*a*).

L'hypothèse que les plaines abyssales sont formées par des coulées de lave sous-marines est basée sur l'existence des plaines et la dureté du fond sous-marin, dureté qui a été indiquée par l'impossibilité d'entrer le carottier en de nombreux endroits pendant l'expédition Suédoise de l'*Albatross* (**Pettersson**, 1953). L'*Albatross* a carotté dans les plaines de l'Atlantique sans difficultés excessives et au moins 10 des échantillons contiennent des faunes déplacées indiquant des dépôts par courants de turbidité (**Phleger**, **Parker** et **Peirson**, 1953). Dans le Pacifique on n'a pas traversé de plaines abyssales; la zone plate découverte « au nord-ouest de la Nouvelle-Guinée » (**Koczy**, 1954) semble être un support d'archipel selon la définition de l'auteur, et on l'a carottée. La force de l'argument par conséquent vient du fait que dans la partie Est de l'Océan Indien, l'expédition a trouvé une grande plaine plate et a cassé un tube de carottier en un endroit (**Pettersson**, 1953) et n'a pu obtenir d'échantillon en un autre point. La plaine plate était coupée en quelques endroits par des abîmes qui ont été identifiés comme étant des fossés coupant la plaine de lave (**Koczy**, 1954). L'hypothèse d'une plaine de lave semble raisonnable si l'on ne tient compte que des renseignements donnés par ce seul écho-sondage et des quelques stations de carottage. A la lumière de recherches plus étendues et plus détaillées dans le Pacifique et l'Atlantique, sela semble improbable.

Actuellement, l'Atlantique Nord et le Pacifique Nord-Est sont les parties des fonds océaniques profonds qui ont été le mieux étudiées avec des instruments capables de détecter les plaines abyssales. Une plaine abyssale existe au large de tout endroit où le fond profond sous-marin est rattaché au continent par une pente continue dirigée vers le large. Dans la partie Est de l'Océan Indien, moins connue, la zone au Sud de la Baie du Bengale est aussi rattachée au continent par une pente continue dirigée vers le large (**Dietz**, 1953). Dans l'Atlantique et le Pacifique, les pentes continues et les plaines abyssales sont traversées par de longs chenaux de mer profonde. Dans la partie Est de l'Océan Indien, les « fossés », connus par une seule coupe, sont identiques en taille et en forme aux chenaux profonds que l'on trouve ailleurs. Les plaines sédimentaires de l'Atlantique et du Pacifique qu'on a fréquemment carottées ont parfois fait plier les tubes de carottier ou sont même impossibles à carotter (Nord Atlantique, **Heezen**, **Ewing** et **Ericson**, 1955) si bien que le fait d'avoir cassé un tube de carottier dans l'Océan Indien n'a pas de signification. En définitive, les plaines abyssales de l'Atlantique et du Pacifique sont recouvertes par plusieurs centaines de mètres d'épaisseur de sédiments. Le H.M.S. Challenger, dans son expédition de 1950-1952, a fait des mesures séismiques de réfraction dans la plaine abyssale de la partie Est de l'Océan Indien. A la station 25 le sédiment avait 550 à 790 mètres d'épaisseur. A la station 26 il en avait 1830 (**Gaskell** et **Swallow**, 1953). La plaine abyssale de la partie Est de l'Océan Indien a donc toutes les caractéristiques des plaines abyssales que l'on rencontre ailleurs, et par conséquent a probablement la même origine.

La distribution et l'extension des plaines abyssales semblent montrer l'importance des courants de turbidité dans la mer. Les continents ont une capacité relativement illimitée de produire des sédiments, et les océans ont une capacité illimitée de les recevoir, mais dans la plupart des endroits, dans le Pacifique Nord, les déplacements de sédiments ont été insuffisants pour aplanir le fond de la mer. Partout où des fosses, des arcs d'îles ou des bassins de la bordure continentale (continental borderland) se

(994)

trouvent entre le continent et la mer profonde, le fond de la mer est accidenté. Les courants de turbidité ne peuvent apporter de sédiments à la mer profonde dans de telles zones. Dans les endroits où il n'existe pas de barrières gênant les courants de turbidité, il semble que ces courants ont transporté de grandes quantités de sédiments qui ont enterré les terrains accidentés préexistants et ont ainsi formé les plaines abyssales.

Supports d'archipels

Qualitativement la formation des supports d'archipels ressemble à celle des plaines abyssales; quantitativement cependant, ces formations suggèrent une origine différente :

1) Les carottages relativement peu nombreux dont on peut disposer montrent que au moins les 3 à 6 mètres supérieurs du matériau d'enfouissement sont sédimentaires.

2) Des mesures séismiques dans le Pacifique indiquent que le sédiment des supports d'archipels peut atteindre par place plusieurs centaines de mètres d'épaisseur mais qu'il n'est pas beaucoup plus épais que dans les points situés loin de toute influence de l'archipel et où le fond est accidenté. L'épaisseur de lave en dessous du sédiment, toutefois, est nettement plus épaisse sous les îles et les supports d'archipels que partout ailleurs dans le bassin (Raitt, Comm. pers., 1952; Gaskell, 1954). Hess (1954) suggère l'existence d'une couche ou « lentille » de lave sous les groupes d'îles.

3) On retrouve dans les supports d'archipels la plupart des faits montrant que les courants de turbidité sont actifs dans les plaines abyssales. Les carottages contiennent des quantités anormales de sédiments grossiers et de faunes déplacées (Revelle et al., 1955); des chenaux de mer profonde traversent ces supports d'archipels; et le sédiment est endigué (Menard, 1956).

Les courants de turbidité ont transporté du matériau provenant des îles le long des pentes volcaniques sous-marines et à travers les grands fonds, et ont ainsi aidé à construire les supports. Des mesures séismiques montrent que leur contribution n'est pas très importante. Si les îles étaient une bonne source de sédiments proportionnelle au volume du matériau formant ces supports, la totalité du support pourrait être produite par les dépôts de courants de turbidité. Des calculs grossiers (Menard, 1956), cependant, indiquent que le volume minimum de quelques-uns de ces supports peut être de 30 à 60 fois plus grand que le volume maximum des îles avant l'érosion. Le terrain préexistant dans les zones d'archipel a apparemment été recouvert d'abord par une couche ou lentille de lave que l'on trouve dans les profils séismiques. Des coulées de fissures ou des coulées provenant de larges dômes ont des pentes de surface très faibles, de l'ordre de 0,003 à 0,006 (Russel, 1902) avec de très petites irrégularités de seulement quelques dizaines de pieds. Toutefois, la pente du support d'archipel des Marquises, dans sa partie comprise entre 110 et 220 km au large, a une moyenne inférieure à 0,002 et, pour les 20 milles plus au large, cette moyenne est d'environ 0,002. On ne connait pas de coulée de lave qui puisse être aussi proche de l'horizontale. Evidemment, les courants de turbidité ont effacé les plus petites irrégularités dans la surface de la lave et ont parfait le nivelage de la partie la plus éloignée du support.

Aplanissements pélagiques

Selon les mesures séismiques de Raitt (Revelle et al., 1955) l'épaisseur de sédiments dans la zone de boue calcaire équatoriale du Pacifique Est est d'environ 400 mètres. La couche n'a pas complètement enterré le relief antérieur, et n'a pas encore comblé les bassins entre les collines (Fig. 2). Le faible relief dans cette région a cependant une forme caractéristique, adoucie et arrondie qui peut être le résultat de l'effet d'une pluie de sédiments pélagiques durant depuis des millions d'années. Une sédimentation continue produirait éventuellement une plaine nivelée si les formations des collines et des montagnes ne se renouvelaient pas et si l'enfoncement local déplaçait les sédiments du haut vers le bas. Une telle plaine ne présenterait pas les caractéristiques d'une zone de dépôt de courants de turbidité telles que les grands chenaux de mer profonde, les pentes très douces et très graduelles qui proviennent ostensiblement de sources sédimentaires, et les matériaux terrigènes loin de terre. Pour autant que les plaines abyssales et les supports d'archipels que nous connaissons ont ces caractéristiques, on peut conclure qu'ils n'ont pas été formés par sédimentation pélagique.

Importance relative des agents d'aplanissement

Trois processus tendent à aplanir le fond des océans :

1) Le glissement local et le transport par courants de turbidité de sédiments provenant des collines et descendant dans les fosses. Les sédiments sont d'abord déposés sur les hauteurs par la chute de matériau pélagique.

2) Le transport par courant de turbidité de grandes quantités de sédiments provenant des continents et pouvant se faire sur des distances allant jusqu'à 1.000 à 2.000 km pour former des plaines abyssales. Une beaucoup plus faible quantité de sédiments est transportée de la même manière à 100 ou 200 km des îles pour former une partie des supports d'archipels.

3) Des extrusions de lave provenant de fissures et de dômes très bas (rattachés génétiquement à des groupes d'îles) forment la plus grande partie du volume des supports d'archipels.

On peut avoir une mesure de l'importance relative de ces processus en comparant les surfaces de chacune des régions qui ont été aplanies. L'estimation des surfaces totales (Tableau I) comprend l'estimation des zones de quelques plaines abyssales individuelles et de remontées continentales qui ne sont connues que par une ou deux transversales de sondage. Une plus grande source d'erreur encore provient de ce qu'on doit supposer l'existence de plaines abyssales dans des zones où il n'y a pas eu de sondages par écho à grande échelle. Pour le but que nous poursuivons actuellement, ceci a été fait en supposant qu'il existe des plaines abyssales dans tout bassin important relié au continent par une pente continue, du moment que les sondages par point qu'on peut avoir ne montrent pas de reliefs appréciables (Fig. 3).

Les surfaces de ces plaines hypothétiques ont été calculées en supposant que les plaines ont une pente dirigée vers le bas, et que tout surélèvement général du fond est accidenté. D'après cette hypothèse, les plaines abyssales connues ont une surface de $15,1 \times 10^6$ km²; les plaines hypothétiques couvrent $7,7 \times 10^6$ km²; les supports d'archipels connus occupent $11,7 \times 10^6$ km², et les supports hypothétiques $2,0 \times 10^6$ km².

Si on tient compte de toutes les sources d'erreurs possibles dans ces estimations, la conclusion la plus certaine qui s'impose est que les plaines abyssales et les supports d'archipels couvrent à peu près la même surface, l'avantage étant plutôt du côté des plaines. Par conséquent, les zones profondes enterrées primitivement par l'extrusion de flots de lave provenant de dômes ou de fissures ont à peu près la même surface que les zones primitivement enterrées par les sédiments transportés par les courants de turbidité, sédiments provenant des continents et transportés sur de longues distances.

La surface totale du fond des mers aplanie par des glissements locaux et les courants de turbidité ne peut être calculée, mais elle est faible par rapport aux surfaces

TABLEAU I

Calculs préliminaires des zones de fonds marins abyssaux plats et proportion de ces surfaces plates par rapport à la surface totale au-dessous de 4.000 mètres pour chaque Océan (SVERDRUP, JOHNSON et FLEMING, 1946, p. 21).

Les supports et les plaines qualifiées de « hypothétiques » se trouvent dans des régions dont on ne possède pas d'enregistrements de sondage.

	Surfaces	% de surfaces plates par rapport aux surfaces des fonds au-dessous de 4.000 m
Océan Pacifique.		
Supports d'archipels	11,7	10,6
Supports d'archipels hypothétiques	2,0	1,8
Total des supports	13,7	12,4
Plaines abyssales	4,0	3,6
Plaines abyssales hypothétiques	1,0	0,9
Total des plaines	5,0	4,5
Total pour le Pacifique	18,7	16,9
Océan Atlantique.		
Plaines abyssales	6,7	13,9
Plaines abyssales hypothétiques	5,4	11,1
Total pour l'Atlantique	12,1	25,0
Océan Indien.		
Plaines abyssales	4,4	10,2
Plaines abyssales hypothétiques	1,3	3,1
Total pour l'Océan Indien	5,7	13,3

connues des plaines abyssales et des supports d'archipels. On ne connait aucune région plate ayant été formée de cette manière, mais, à l'intérieur de zones généralement accidentées il existe de nombreux bassins à fond plat ayant quelques milles de large qui n'ont pas d'autre source de remplissage.

Les différents agents d'aplanissement du fond marin sont génétiquement indépendants et n'ont été séparés que pour la facilité de la discussion, mais plusieurs agents peuvent agir concuremment dans la même zone. Les supports d'archipels sont en grande partie formés par de la lave, mais la perfection de l'aplanissement indique qu'il y a eu aussi un dépôt par courant de turbidité.

Des successions de bancs de lave et de sédiments sont indiquées par comparaison des études séismiques de réflexion et de réfraction faites dans la plaine abyssale à l'Ouest des Bermudes (Officer, 1955).

Bibliographie

Browne, B. C. (1954). Gravity measurements and oceanic structure. *Royal Soc., Proc.*, ser. A, *222*, 398-400.

Dietz, R. S. (1953). Possible deep-sea turbidity-currents channels in the Indian Ocean. *Geol. Soc. America Bull.*, *64*, 375-378.

Ericson, D. B., Ewing, Maurice, and Heezen, B. C. (1952). Turbidity currents and sediments in North Atlantic. *Amer. Assoc. Petroleum Geologists Bull.*, *36*, 489-511.

Ericson, D. B., Ewing, M., Heezen, B. C., and Wollin, G. (1955). Sediment deposition in deep Atlantic. *Geol. Soc. America Spec. Pap.*, *62*, 205-220.

Ewing, M., Heezen, B. C., Ericson, D. B., and Dorman, J. (1953). Exploration of the northwest Atlantic mid-ocean canyon. *Geol. Soc. America Bull.*, *64*, 865-868.

Ewing, Maurice, Sutton, G. H., and Officer, C. B., Jr. (1954). Seismic refraction measurements in the Atlantic Ocean, Part VI : Typical deep stations, North America Basin. *Seismological Soc. America Bull.*, *44*, 21-38.

Ewing, Maurice, Worzel, J. L., Ericson, D. B., and Heezen, B. C. (1955). Geophysical and geological investigations in the Gulf of Mexico. Pt. I, *Geophysica*, *20*, 1-18.

Gaskell, T. F. (1954). Seismic refraction work by *H.M.S. Challenger* in the deep oceans. *Royal Soc., Proc.*, ser. A, *222*, 356-361.

Gaskell, T. F., and Swallow, J. C. (1953). Seismic refraction experiments in the Indian Ocean and in the Mediterranean Sea. *Nature*, *172*, 535.

Heezen, B. C., Ewing, Maurice, and Ericson, D. B. (1954). Reconnaissance survey of the abyssal plain south of Newfoundland. *Deep-Sea Research*, *2*, 122-133.

Heezen, B. C., Ewing, M., and Miller, E. T. (1953). Trans-Atlantic profile of total magnetic intensity and topography, Dakas to Barbados. *Deep-Sea Research*, *1*, 25-33.

Menard, H. W. (1955*a*). Deep-sea channels, topography, and sedimentation. *Amer. Assoc. Petroleum Geologists Bull.*, *39*, 236-255.

Menard, H. W. (1955*b*). Deformation of the northeastern Pacific basin and the west coast of North America. *Geol. Soc. America Bull.*, *66*, 1149-1198.

Menard, H. W. (1956). Archipelagic aprons. *Amer. Assoc. Petroleum Geologists Bull.*, *40*, 2195-2210.

Menard, H. W., and Dietz, R. S. (1951). Submarine geology of the Gulf of Alaska. *Geol. Soc. America Bull.*, *62*, 1263-1285.

Officer, C. B. (1955). Geologic interpretation of a series of seismic reflection profiles from Bermuda to the continental margins. *Deep-sea Research*, *2*, 253-260.

Pettersson, H. (1953). Westward Ho with the Albatross. New-York, E. P. Dutton & Co., Inc. 218 p.

Phleger, F. B., Parker, F. L., and Peirson, J. F. (1953). North Atlantic Foraminefera. *Swedish Deep Sea Expedition, Repts.*, *7*, no. 1, 1-122.

(998)

Revelle, R., Bramlette, M., Arrhenius, G., and Goldberg, E. D. (1955). Pelagic sediments of the Pacific. *Geol. Soc. America Spec. Pap., 62*, 221-236.

Russell, I. C. (1902). Geology and water resources of the Sanke River Plains of Idaho. *U.S. Geol. Surv. Bull., 199.*

Shepard, F. P. (1933). Depth changes in Sagami Bay during the great Japanese earthquake. *Jour. Geology, 41*, 527-536.

Shepard, F. P. (1948). Submarine geology. New-York, Harper and Brothers, 348 p.

Shepard, F. P., and Emery, K. O. (1941). Submarine topography of the California coast. *Geol. Soc. America Spec. Pap., 31*, 171 p.

Sverdrup, H. U., Johnson, M. W., and Fleming, R. H. (1946). The oceans. New-York, Prentice-Hall, Inc., 1087 p.

DISCUSSION

M. Heezen comprend difficilement pourquoi le conférencier affirme que les volcans ne peuvent avoir été érodés au cours de leur activité car, dans ce cas, ils auraient pu reconstituer un certain nombre de fois leur propre volume.

M. Glangeaud, notant que l'auteur a indiqué qu'il y avait probablement à la base des îles des couches de laves, demande quels sont les arguments en faveur de cette hypothèse.

M. Emery. — Des prospections sismiques et gravimétriques ont permis de le prouver.

M. Glangeaud demandant si des profils magnétiques ont été effectués, le conférencier répond qu'il n'a pas d'opinion sur les résultats que l'on pourrait obtenir de ces mesures.

M. Emery précise que le volcan serait à cheval sur la bande décrite et M. Gaskell avance que ce doit être un volcan très jeune qui n'a pas encore été affecté de subsidence.
A la suite d'une demande de M. Glangeaud sur l'épaisseur de la bande et sur l'affirmation qu'elle atteindrait 5 km de puissance dans tout le Pacifique, M. Gaskell dit que cette généralisation est exagérée. Dans le NE de la Nouvelle Zélande, elle peut atteindre 15 à 20 km. Il n'y a qu'un seul point dans le Pacifique où cette couche est beaucoup plus mince, réduite à 3 km, c'est au large de l'Amérique du Sud où on a observé une topographie sous-marine analogue à celle de l'Atlantique.

M. Glangeaud ayant fait préciser que la profondeur minimum de la coulée de lave des archipels était de 4 000 mètres par rapport à la surface de la mer, insiste sur le fait que toute *éruption* est impossible dans ces conditions.

M. Menard ajoute que c'est pourquoi lui-même est arrivé à la conclusion qu'il s'agissait de laves fluides.

M. Dietz désirerait connaître l'opinion de M. Glangeaud au sujet de la pression maximum permettant la production d'explosions volcaniques.

M. Glangeaud. — En principe, elle doit être inférieure à la pression critique de la vapeur d'eau. Car au-dessus, il n'y pas explosion comme le démontrent les travaux de M. Goguel. Le calcul théorique donne une valeur de 3 200 m.

M. Gaskell. — Quel type de surface plate rencontre-t-on dans l'Océan Indien ?

M. Emery. — Ce sont des plaines abyssales avec des épaisseurs de sédiments de 300 à 1 800 m.

M. Glangeaud demandant si on a fait des prospections pour déterminer quelle était la nature de la couche de sédiment dans l'Océan Indien, M. Gaskell répond qu'il a entrepris des mesures sismiques. Elles ont mis en évidence une structure semblable à celle du Pacifique. Au Sud de l'Equateur, dans l'Est de l'Océan Indien, certaines structures ont donné des résultats confus par suite de la présence de montagnes sous-marines. Il suppose donc qu'il s'agit d'un archipel.

M. Glangeaud. — Quelle est la vitesse de transmission des couches situées au-dessous du sédiment superficiel ?

M. **Gaskell**. — 2, 1 à 4, 5 et 6, 7 km/s selon la profondeur.

M. **Landergren**. — Il y a une différence entre la nature des sédiments dans les Océans Indien et Pacifique. Dans le Pacifique, le substratum est plutôt basique, tandis qu'il est acide dans l'Océan Indien.

M. **Bourcart** fait remarquer qu'il y a une grande différence entre les secteurs occidental et oriental de l'Océan Indien.

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Action Spectra for Two Effects of Light on Luminescence in *Gonyaulax polyedra*

B. M. SWEENEY, F. T. HAXO, and J. W. HASTINGS

ABSTRACT The luminescence of the marine dinoflagellate *Gonyaulax polyedra* shows an endogenous diurnal rhythm. The effect of light during the phase of low luminescence capacity may be observed as an enhancement of luminescence during the subsequent bright phase. During the bright phase, however, illumination diminishes the capacity for luminescence. The action spectra for these two effects of light have been determined, and the major pigments of *Gonyaulax* have been examined. A consideration of the action spectrum and the pigment complement of *Gonyaulax* suggests that photosynthesis during the day is responsible, directly or indirectly, for the enhancement of luminescence during the following night. Photoinhibition of luminescence is in part attributable to light absorbed by the photosynthetic pigments. However, activity observed in the far red region of the spectrum beyond the absorption maximum of chlorophyll *a* suggests that an additional pigment, present in small amounts, may also act as sensitizer for photoinhibition.

INTRODUCTION

The photosynthetic marine dinoflagellate, *Gonyaulax polyedra*, is one of many organisms which contribute to the "phosphorescence" of the sea. The bioluminescence of laboratory cultures of this dinoflagellate has been the subject of a series of studies by the authors, in which the general features of this process have been described (Haxo and Sweeney (1955); Sweeney and Hastings (1957); Hastings and Sweeney (1958)).

Measurements of the luminescence of cell suspensions under a variety of conditions demonstrated early in the course of these studies that light affects the intensity of luminescence. Two types of light effects have been observed. First, it was apparent that light inhibits luminescence. Second, the intensity of luminescence proved directly dependent on the light intensity during preillumination. In the present study, the action spectra for these two effects

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were determined in an effort to identify the sensitizing pigments and to establish the relationships of these effects to other physiological processes.

A number of observations have led to the postulation that luminescence in *Gonyaulax polyedra* is an expression of diurnal endogenous rhythmicity (Sweeney and Hastings (1957); Hastings and Sweeney (1958)). The general features of this intrinsic rhythmicity which must be taken into consideration in determining the effects of light on luminescence capacity are summarized

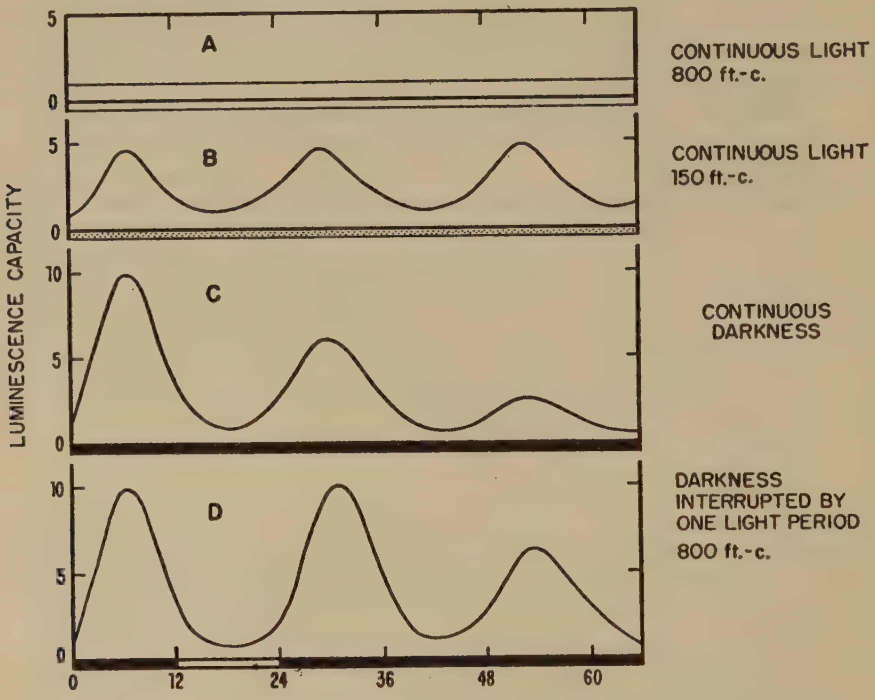

FIGURE 1. Diagrammatic representation of the changes in luminescence capacity of *Gonyaulax polyedra* taken from continuous bright light (800 foot-candles) and maintained at the same temperature (20°C.) in the light and dark regimes indicated by bars along the abscissa. In curve A, the cells remained in bright light; in curve B, the light intensity was reduced to 150 foot-candles at 0 hours; in curve C, the cells were transferred to darkness at 0 hours; and curve D, darkness was interrupted with a single light period (800 foot-candles) between 12 and 24 hours. The difference in the magnitude of the luminescence capacity of the first cycles of curves B and C exemplifies the inhibitory effect of light of intermediate intensities comparable to those employed in determining the action spectrum of photoinhibition. The maximum light inhibition obtainable is represented in curve A. The differences in the magnitude of luminescence capacity at comparable times during the second cycles of curves C and D illustrate the photoenhancement brought about by the preceding light period in curve D.

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in Fig. 1. All the curves represent luminescence in cells grown in continuous bright light. When this treatment is continued (Fig. 1, curve A), luminescence remains at a constant low value with no manifestation of rhythmicity. However, on placing such cell suspensions in light of lower intensity (Fig. 1, curve B), the endogenous rhythm of luminescence becomes apparent. On transferring cells to darkness, (Fig. 1, curve C), the luminescence capacity also shows rhythmicity, but the amplitude of the rhythm decreases with each successive cycle. If a light period intervenes between the first and second maximum in luminescence (Fig. 1, curve D), the decrease in amplitude of the following cycle is prevented. The difference in luminescence capacity of the first cycles of curves B and C is a measure of the inhibitory effect of light of medium intensity on the luminescence capacity. Maximum photoinhibition is depicted in curve A. The difference in the magnitude of the luminescence capacity at comparable times during the second cycles of curves C and D illustrates the photoenhancement brought about by the preceeding light period in curve D.

In contrast to the luminous bacteria and fungi which emit light continuously, bright luminescence in *Gonyaulax polyedra* is a response to mechanical stimulation.[1] When cell suspensions are vigorously agitated, luminescence is virtually exhausted during the first minute of stimulation. The term luminescence as used in this study refers in all cases to light emission integrated over the first minute of stimulation.

Methods

MATERIAL For this investigation, unialgal cultures of *Gonyaulax polyedra* were grown in Fernbach flasks at 20°C. with illumination from "cool white" fluorescent lamps at an intensity of about 1000 foot-candles. These lamps were on continuously for 12 hours during each 24 hour period, thus making "day" and "night" 12 hours each. Cultures were inoculated at a cell density of about 300 cells per ml. The volume of each culture was 1500 ml. On the day prior to experimental light treatments, 2 ml. aliquots from a culture were distributed into a number of 12 × 120 mm. pyrex test tubes and maintained in alternating light and darkness until the beginning of the experiment.

The culture medium was composed of 75 per cent filtered sea water, 2 per cent soil extract (Pringsheim (1946)), 2×10^{-3} M KNO_3, 2×10^{-4} M K_2HPO_4, 6×10^{-6} M $FeCl_3$, and 2.7×10^{-5} M ethylenediamine tetraacetic acid (EDTA) at pH 8.0–8.2.

LIGHT SOURCES AND IRRADIATIONS In experiments in which cell suspensions were irradiated with white light, the light source was a bank of cool white fluorescent lamps similar to those used to illuminate cultures during growth. The intensity of white light was measured with a foot-candle meter (Weston model 756) or with an

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[1] In addition, a very faint glow may be detected with extremely sensitive instrumentation.

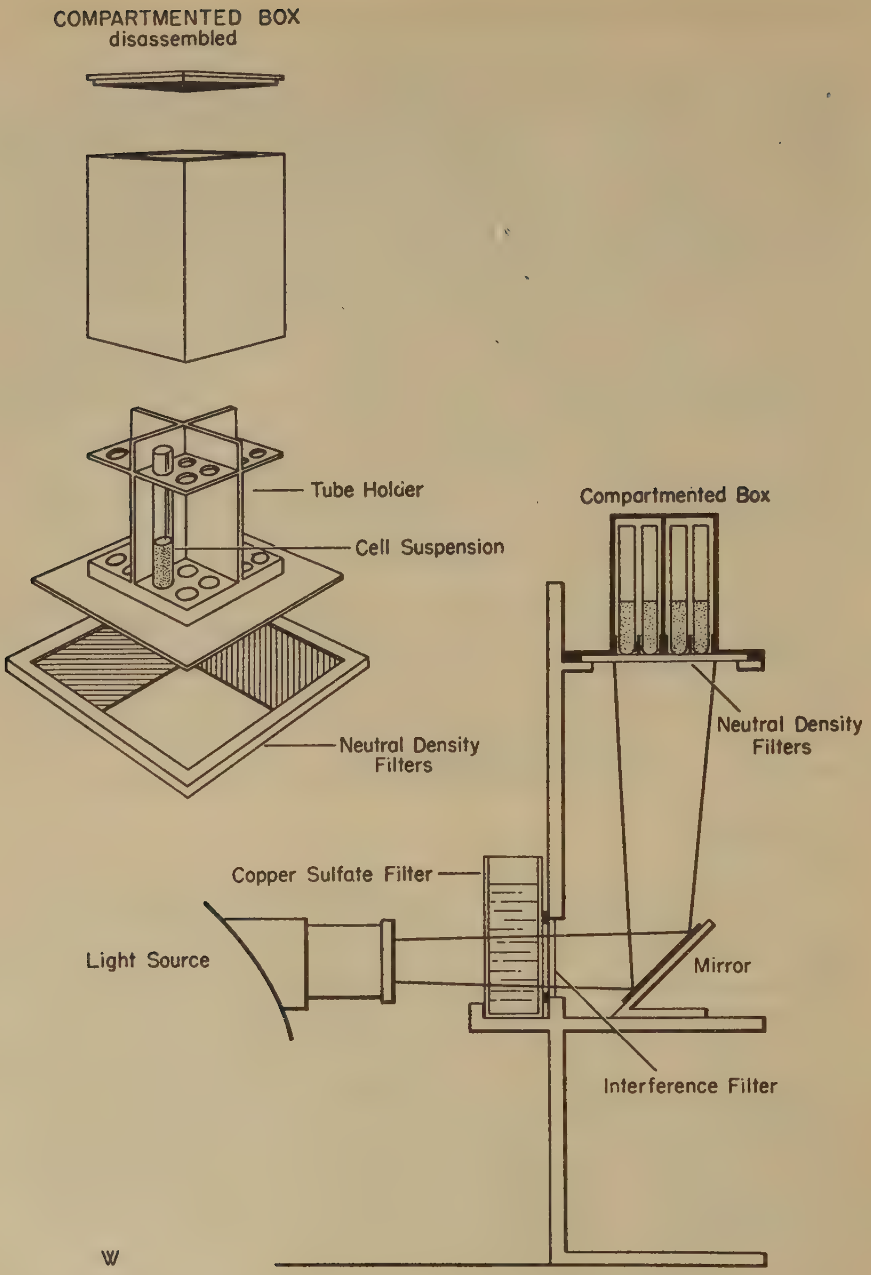
COMPARTMENTED BOX
disassembled
Tube Holder
Cell Suspension
Neutral Density
Filters
Compartmented Box
Neutral Density
Filters
Copper Sulfate Filter
Light Source
Mirror
Interference Filter
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FIGURE 2. Schematic diagram of the optical system employed for the determination of the action spectra of photoenhancement and photoinhibition of luminescence capacity drawn slightly off the median plane to show two compartments and the positioning of four of the sixteen tubes. Box, tube holders, and shielding were of black plastic. Three such units were used with three different interference filters, providing simultaneous irradiation at three wave lengths.

Eppley thermopile. The measured conversion factor for this light source, with a 5 cm. layer of water inserted in the light path, was 46.5 ergs per cm.² per sec. per ft.-candle. Different intensities of white light were obtained either by varying the distance between the lamps and the cell suspension or by interposing in the light path crossed polaroid films.

Monochromatic light was obtained by using interference filters (Balzers). These were found to transmit about 40 per cent of the incident light at the wave length of maximum transmission and to have a half-band pass ranging from 9 to 15 mμ and averaging 11 mμ. Three 1000 watt slide projectors, each with a 5 inch focal length f2.3 lens system, were used as light sources, the intensities being adjustable by a variable transformer. The divergence of the emergent beam was about 7°. As shown in Fig. 2, the optical system included, in sequence, a 5 cm. path of acidified 0.02 M $CuSO_4$,[2] an interference filter, and a front-surfaced mirror set at an angle of 45° to the axis of the light beam. The latter was thus directed onto a compartmented container for simultaneous irradiation at four light intensities, achieved by facing the lower surface of each compartment with different neutral density filters (Wratten). Each compartment accommodated four test tubes.

Light intensities were measured with a photronic cell (Weston model 856, type RR), in conjunction with a microammeter. The photronic cell was masked to the cross-sectional dimensions of a test tube and provided with a collar extending to the position normally occupied by the samples during irradiation. The photronic cell was calibrated in ergs per sec. per cm.² for each interference filter in the optical system described above, using an Eppley thermopile and a standard lamp. All experiments were performed in a constant temperature room at 20 ± 1.5°C.

MEASUREMENTS OF LUMINESCENCE Luminescence was measured with a photomultiplier photometer which integrates the light emitted (Sweeney and Hastings (1957)). The cells were stimulated (Fig. 3) to emit light by bubbling air through the cell suspension for 1 minute, by which time virtually all luminescence has ceased. Recovery subsequent to stimulation is slow and varies under different conditions, hence different aliquots from the same cell suspension were always used to assess luminescence.

PIGMENT STUDIES The fat-soluble pigments were extracted from *Gonyaulax* cells with methanol and separated chromatographically on columns of powdered sucrose, according to the method of Strain *et al.* (1944). From their characteristic absorption spectra in several solvents, chlorophyll *a* and chlorophyll *c* were identified as the only green pigments, and peridinin as the predominant carotenoid. The composition of the *Gonyaulax* carotenoids was not investigated further, although the presence of other components was noted.

The absorption curve of the total fat-soluble pigment was determined in methanol with an aliquot from the original extract. Since attempts to fractionate this extract quantitatively proved unsuccessful, largely due to the difficulty in separating chlorophyll *c* and the polyoxy carotenoids, the contributions of individual pigments or groups of pigments to the total absorption of the extract, as shown in Fig. 6, were estimated as follows. The absorption curves determined for chromatographically separated chlorophyll *a* and chlorophyll *c* in methanol were replotted to provide the best fit of their summated absorptions to that of the total pigment extract in the red region of the spectrum. The absorption of the total carotenoid fraction could then be derived as the residual absorption of the total pigment extract not attributable to chlorophylls. Through the quantitative fractionation of the carotenoids from *Gonyaulax*, it was found that all of the absorption of carotenoid fractions at wave lengths greater than 525 mμ was accounted for by peridinin. The contribution of peridinin

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[2] Water was substituted for $CuSO_4$ solution when interference filters transmitting light of wave lengths longer than 705 mμ were used.

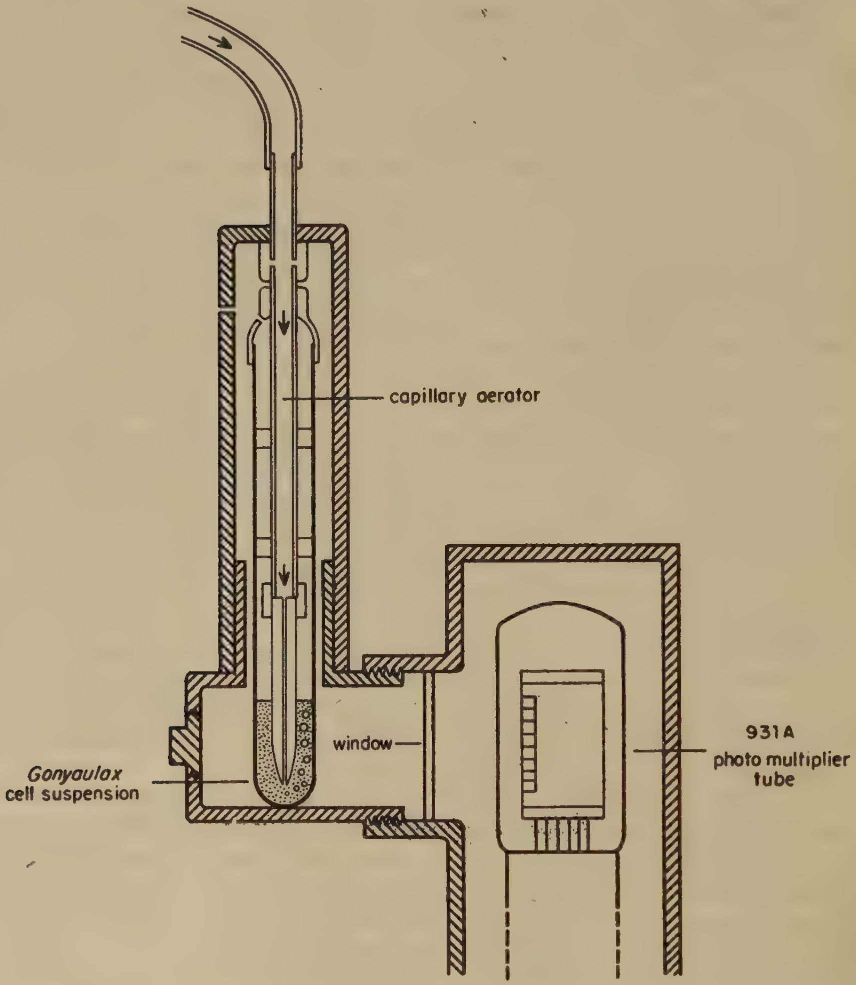

FIGURE 3. Schematic diagram of the apparatus used for stimulating luminescence in *Gonyaulax* by aeration and for detecting the light emitted.

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to the absorption of the corresponding total extract was therefore estimated by normalizing at this wave length. All absorption curves were determined in detail with a Beckman DU spectrophotometer.

The absorption of intact *Gonyaulax* cells was determined with a concentrated cell suspension, employing the opal glass technique of Shibata, Benson, and Calvin (1954). Settling of the living cells during the measurement was avoided by increasing the viscosity of the suspending nutrient medium by adding a small amount of cellulose gum.[3]

Experimental Results

PHOTOENHANCEMENT OF LUMINESCENCE The general features of photoenhancement of luminescence were determined in preliminary experiments with white light. The cell suspensions used for this study were from cultures of *Gonyaulax* which, during the preceding 4 day growth period, had been illuminated during the light period with white light of 200 foot-candle intensity. During the subsequent 12-hour light period, controls received no illumination while experimental samples were exposed to illumination of various intensities and durations. All light exposures terminated at the same time. The luminescence was measured 5 to 7 hours after the end of the light period. The increase in luminescence subsequent to illumination is plotted in Fig. 4. When the data are plotted with light intensity as abscissa (upper graph), it may be seen that in all cases maximum photoenhancement occurred at about 800 foot-candles. At the temperature used (20°C.), photosynthesis also reaches a maximum at about 800 foot-candles (Haxo and Sweeney (1955)).

The magnitude of the increase in luminescence during the dark period is a function of both the intensity and the duration of illumination during the preceding light period. A linear relationship is not observed over the whole range of intensity. It is interesting to note (Fig. 4, lower graph), that 12 hours of illumination caused a disproportionately large increase in luminescence. This observation suggests that light may not be equally effective throughout the light period.

For determining the action spectrum for photoenhancement of luminescence, cells were illuminated for 12 hours with monochromatic light of different spectral regions, and the difference between the luminescence of illuminated and darkened cell suspensions was measured as described above. The light intensities were adjusted to provide equal numbers of quanta (0.24 μ einstein per minute per $cm.^2$) at each wave length band, and were in the range in which effectiveness increases approximately linearly with increasing light intensity. A small correction for deviation from linearity was

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[3] This product was kindly supplied by the Hercules Powder Co., Wilmington, Delaware.

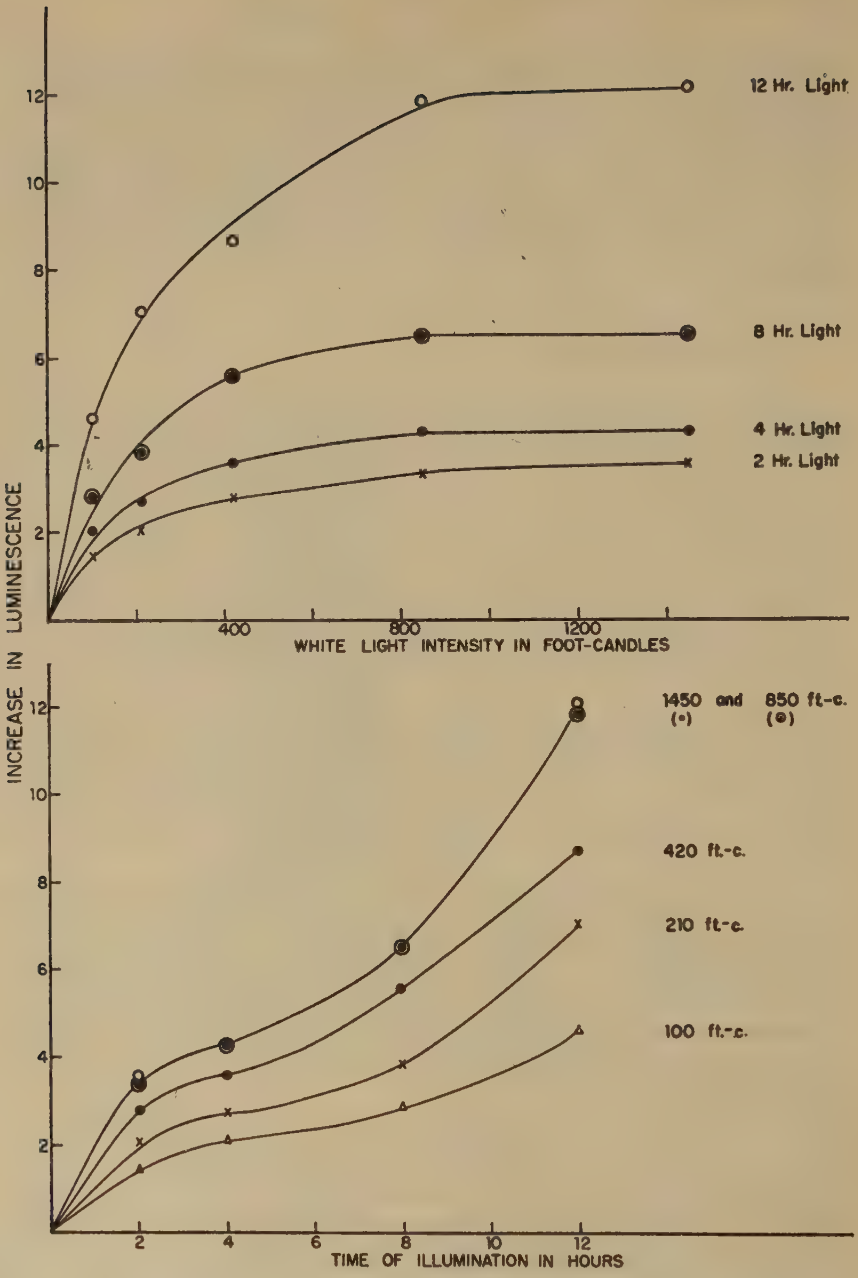

FIGURE 4. Photoenhancement of luminescence capacity of *Gonyaulax polyedra* by white light. Cell suspensions were irradiated during the day, and the luminescence was measured the following night. The ordinate represents increase in luminescence as compared with that of cell suspensions darkened during the day. The abscissas are light intensity in foot-candles (upper graph) and duration of exposure to light in hours (lower graph). Each point represents the average of three to five determinations.

(1008)

applied utilizing the response curve for white light run concurrently and covering a wide range of intensities. The data so obtained are plotted as the action spectrum for photoenhancement of luminescence in Fig. 5, where they are arbitrarily superimposed at 678 mμ on an absorption spectrum for a suspension of *Gonyaulax* cells. Also included are the estimated contributions to absorption by the major pigment fractions at three wave lengths. Detailed absorption curves of the pigments in methanol from which these values were derived are shown in Fig. 6.

It is apparent from Fig. 5 that the action spectrum for photoenhancement bears a resemblance to the absorption of the cell suspension in that activity is high in the red and blue regions in which the chlorophylls absorb strongly and minimal in the regions in which chlorophyll absorption is low. Thus chlorophyll may be implicated as a sensitizer for photoenhancement of luminescence. It would appear also that carotenoids, notably peridinin, are

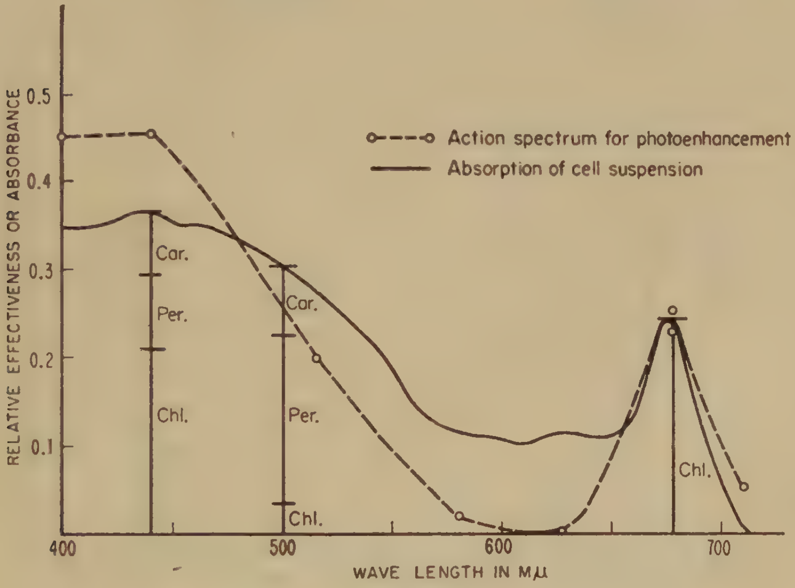

FIGURE 5. Action spectrum for photoenhancement of luminescence capacity in *Gonyaulax polyedra*. An absorption curve of a somewhat concentrated cell suspension is included for comparison, the two curves being arbitrarily superimposed at 675 mμ. The approximate contributions to absorption by peridinin (per.), other carotenoids (car.), and chlorophylls *a* and *c* (chl.) are shown here by vertical bars. The values were derived from the data for methanolic extracts presented in Fig. 6. In order to correct for the effect of the solvent, pigment absorptions at 440 mμ and 500 mμ were shifted toward longer wave lengths as follows: chlorophyll *a*, 7 mμ; chlorophyll *c*, 20 mμ; peridinin, 40 mμ; other xanthophylls, 20 mμ.

sensitizers; otherwise the effectiveness would certainly not be so high in the blue-green region of the spectrum in which, as shown in Figs. 5 and 6, carotenoids account for the major fraction of the absorbed light.

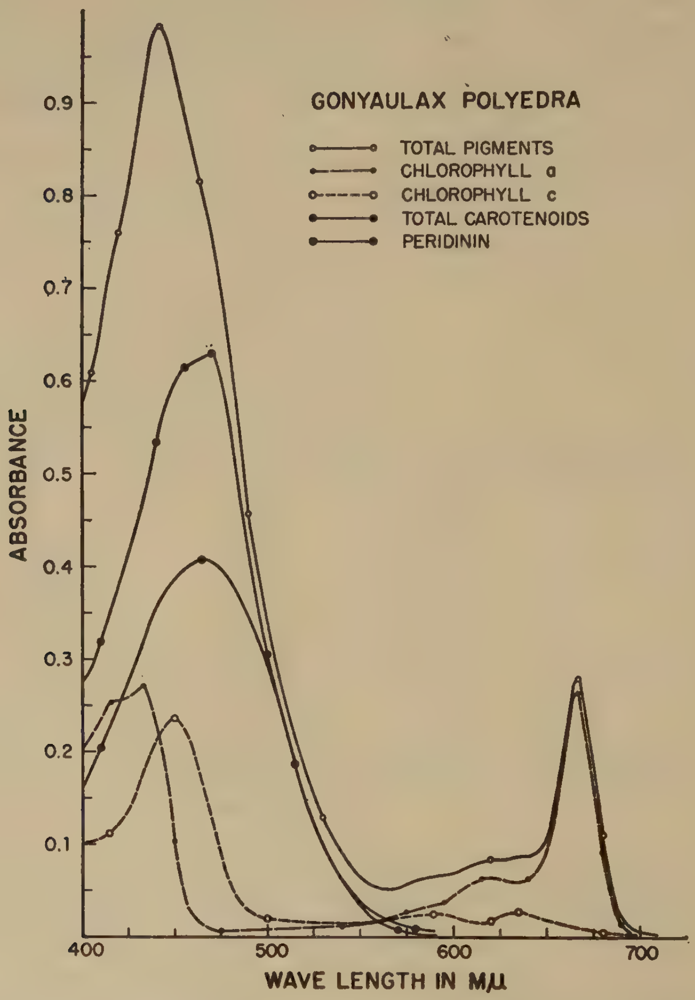

FIGURE 6. The absorption of methanolic extracts of the pigments of *Gonyaulax polyedra*.

PHOTOINHIBITION OF LUMINESCENCE As shown diagrammatically in Fig. 1, curve A, exposure of *Gonyaulax* cells to continuous light of about 800 foot-candle intensity suppresses the rhythm in luminescence, while at intermediate intensities (Fig. 1, curve B), the effect is only partial. Photoinhibition may therefore be measured accurately and conveniently during the increase in luminescence as the difference between the luminescence of illuminated samples and that of dark controls.

The following experimental procedure was adopted: samples from a culture of *Gonyaulax* growing with alternating light and dark periods of 12 hours each were prepared at the beginning of a light period. This light period was prolonged by 2 hours, since it was found in preliminary experiments that such treatment increased the rate at which maximum luminescence was attained during the subsequent dark phase. At the end of this illumination period, a number of samples of the cell suspension were placed under each of the following experimental conditions: (*a*) darkness; (*b*) monochromatic light at several intensities; (*c*) white light at 1000 foot-candles as a measure of the maximum photoinhibition obtainable; and (*d*) white light at 200 foot-candles. The latter provided a measure of the sensitivity of the cells employed. Under the experimental conditions used, the maximum

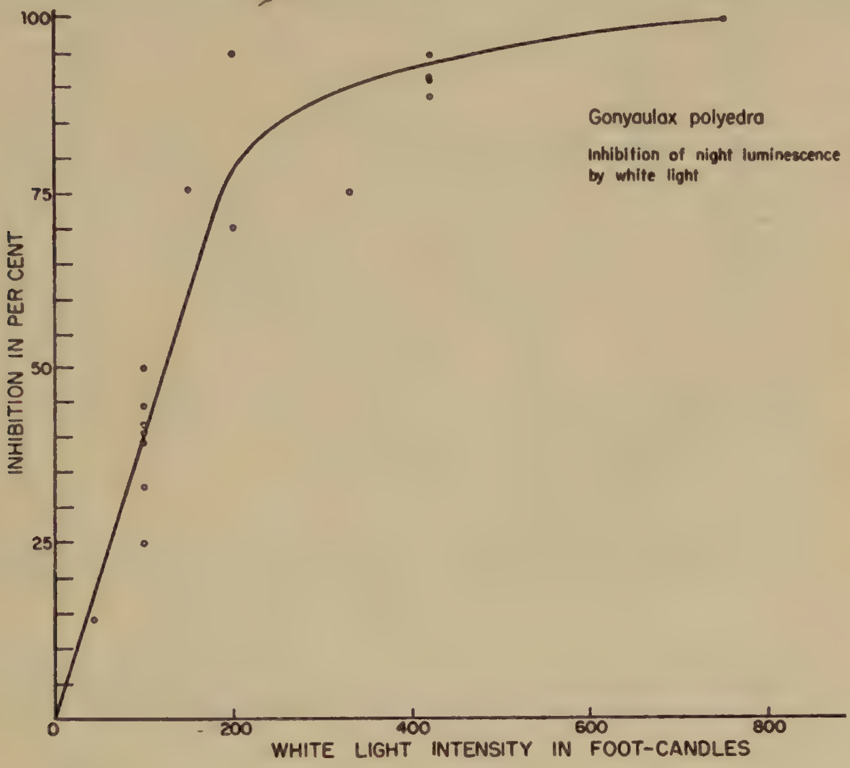

FIGURE 7. The effect of white light of different intensities on photoinhibition of luminescence capacity in *Gonyaulax polyedra*.

luminescence in darkness was about ten times that in 1000 foot-candle white light. Photoinhibition, expressed as per cent of the luminescence of darkened controls, was found to be constant with time. The recording of luminescence in an experimental series usually required about an hour, during which time measurements of the dark controls were interspersed with those of samples which had been irradiated.

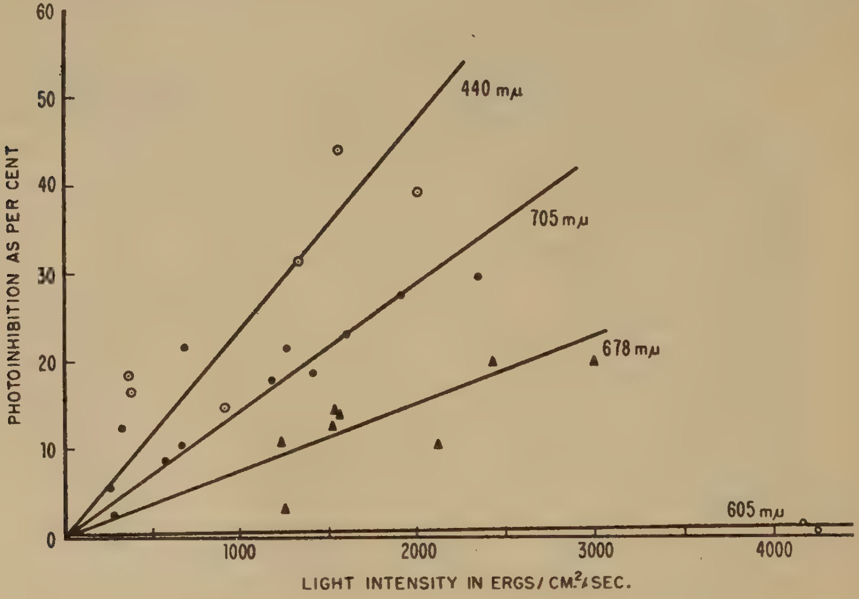

FIGURE 8. Photoinhibition of luminescence capacity in *Gonyaulax polyedra* by monochromatic light of different intensities: (⊙) 440 mμ; (○) 605 mμ; (▲) 678 mμ; (●) 705 mμ. Each point represents a single determination.

When cell suspensions were illuminated with white light of different intensities during the bright phase, the resulting inhibition of luminescence was found to be a function of light intensity (Fig. 7). Photoinhibition, like photoenhancement, is maximal at about 800 foot-candles.

Representative results for the dependence of inhibition upon the incident intensity of monochromatic light are shown for several wave lengths in Fig. 8. It may be noted that the scattering of points shown here was typical and that efforts to reduce this variability were unsuccessful. These and other similar results serve to indicate that the inhibitory effect was linear with intensity for all wave lengths studied. The per cent inhibition was then calculated for equal incident quanta at each wave length with reference to an intensity of 2000 ergs per sec. per cm.² at 440 mμ.

The action spectrum for photoinhibition obtained by plotting these values against wave length is shown in Fig. 9. The curve shows a maximum in activity at about 440 mμ and a minimum close to 600 mμ, being similar in this respect to the action spectrum for photoenhancement. A lower maximum in the red extends broadly from about 660 to 720 mμ, with an apparent peak at about 700 mμ. Activity was low but still measurable at 735 mμ, the longest wave length tested. The results suggest that chlorophyll and perhaps other photosynthetic pigments are the dominant sensitizers in the spectral region 400 to 680 mμ. Because of the marked fall-off in absorption by chlorophyll *a* to negligible absorption beyond 710 mμ, we can only speculate that an unidentified pigment must be acting as the sensitizer for the inhibition of luminescence in the region of 690 to 735 mμ. This must be a minor component, since it does not appear to contribute significantly to the absorption by intact cells.

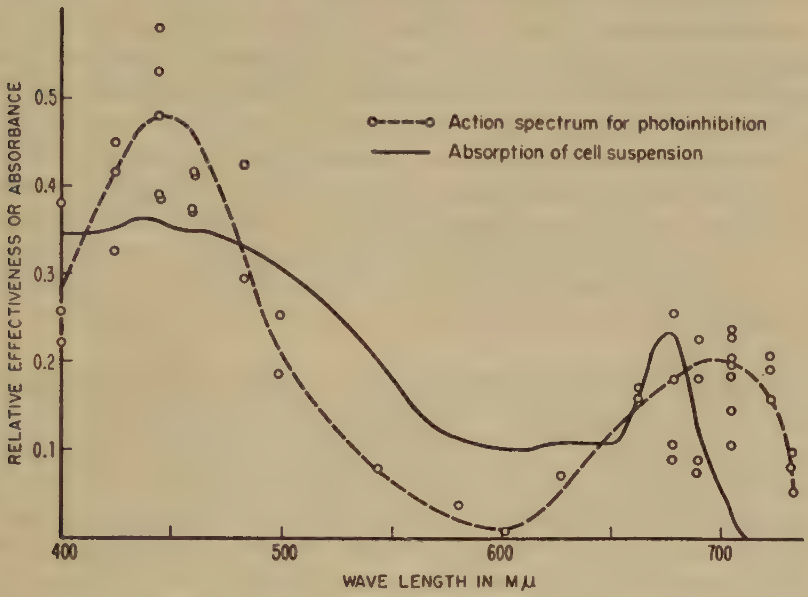

FIGURE 9. The action spectrum for photoinhibition of luminescence capacity in *Gonyaulax polyedra*. Each point is derived from a single experiment as shown in Fig. 8. The absorption spectrum for a cell suspension is included for comparison.

DISCUSSION

Preliminary determinations of the action spectrum for photosynthesis in *Gonyaulax* indicate that both chlorophyll and peridinin are active as sensitizers for photosynthesis (Haxo, unpublished data). Since the action spectrum for photoenhancement of luminescence capacity implicates the same plastid pigments, it is suggested that photoenhancement is mediated through photosynthesis. This suggestion receives additional support from the observation that photoenhancement of luminiscence capacity is maximal at the same light intensity as reported previously for photosynthesis; *i.e.*, about 800 foot-candles at 20°C. (Haxo and Sweeney (1955)).

Photosynthesis is, of course, necessary for the maintenance of any photo-auxotrophic cell such as *Gonyaulax*. Products of photosynthesis, such as short chain carbon compounds and energy-rich molecules, presumably enter the intracellular metabolic pool and storage depots, from which they may be later withdrawn as required for various cellular processes, including luminescence. Although the components involved in the luminescent reaction in *Gonyaulax* are not known at the present time, it is of interest to note that the biosynthesis of the components of the luminescent system apparently takes place during each cycle of the endogenous rhythm, since the levels of luciferin and luciferase in the cell are known to fall during the day and rise at night (Hastings and Sweeney (1957)).

Although between 440 and 660 mμ the action spectrum for photoinhibition of luminescence appears to be very similar to that for photoenhancement, photoinhibition cannot be related to photosynthesis in any simple way because of the activity in the far red region of the spectrum, in which absorption by chlorophyll is negligible. Although an accurate measurement was not possible, the action spectrum may actually have two absorption maxima in the red, with one peak at about 680 mμ and the other at 710 mμ. Two possible interpretations may be considered. It may be that chlorophyll and peridinin sensitization accounts for the activity between 440 and 680 mμ and that still another pigment is responsible for the activity above 680 mμ. It is also possible that the resemblance of the action spectrum for photoinhibition to chlorophyll and carotenoid absorption is fortuitous and that a different pigment present in small amounts accounts for the activity throughout the spectrum.

Light in the region of the visible spectrum beyond 680 mμ is known to produce a number of physiological effects. Notable among these is the promotion of germination in lettuce seeds by light of about 690 mμ (Hendricks and Borthwick (1954)). Effects of this type are reversed by far red light of wave lengths beyond 700 mμ. However, experiments have shown that far red light (720 to 1200 mμ) does not reverse the photoinhibition of luminescence capacity in *Gonyaulax*. Mohr (1957) has reported an effect of red light in the proximity of 700 mμ on anthocyanin formation and the inhibition of hypocotyl elongation in mustard seedlings. These effects are evident at relatively high light intensities and are not reversed by far red light. Evidence has also been presented by Kok (1957) based upon difference spectra concerning the presence, in variously colored algae and higher plants, of a pigment

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which absorbs maximally at 705 mμ to 708 mμ and undergoes changes upon irradiation *in vivo*. However, it cannot be stated at present whether the photoinhibition of luminescence bears any relationship to these effects.

The action spectrum for photoinhibition in *Gonyaulax* may be contrasted with inhibitory effects in other luminescent systems. In the luminous bacterium, *Photobacterium* (Van der Kerk, 1952) and the luciferin-luciferase system of *Cypridina* (Chase and Giese (1940); Harvey (1952)), only the far blue and ultraviolet regions of the spectrum are effective, unless sensitizers such as eosin, riboflavin, or methylene blue are present. Furthermore, exposure to white light does not reduce the intensity of the luminescence of cell-free extracts of *Gonyaulax*, which are prepared from acetone powders and hence largely devoid of fat-soluble pigments. Thus, the photoinhibition of luminescence in *Gonyaulax* cells described here would not appear to be attributable to direct photolability of luciferin and luciferase.

The authors gratefully acknowledge the technical assistance of Mrs. Nao Belser.

BIBLIOGRAPHY

CHASE, A. M., and GIESE, A. C., Effects of ultraviolet radiation on *Cypridina* luciferin and luciferase, *J. Cell. and Comp. Physiol.*, 1940, **16**, 323.

HARVEY, E. N., Bioluminescence, New York, Academic Press, 1952.

HASTINGS, J. W., and SWEENEY, B. M., The luminescent reaction in extracts of the marine dinoflagellate, *Gonyaulax polyedra*, *J. Cell. and Comp. Physiol.*, 1957, **49**, 209.

HASTINGS, J. W., and SWEENEY, B. M., A persistent diurnal rhythm of luminescence in *Gonyaulax polyedra*, *Biol. Bull.*, 1958, **115**, 440.

HAXO, F. T., and SWEENEY, B. M., Bioluminescence in *Gonyaulax polyedra*, *in* The Luminescence of Biological Systems, (F. H. Johnson, editor), Washington, D. C., American Association for the Advancement of Science, 1955, 415.

HENDRICKS, S. B., and BORTHWICK, H. A., Photoresponsive growth, *in* Aspects of Synthesis and Order in Growth, (D. Rudnick, editor), Princeton University Press, 1954, 149.

KOK, B., Light induced absorption changes in photosynthetic organisms, *Acta bot. néerl.*, 1957, **6**, 316.

MOHR, H., Der Einfluss monochromatischer Strahlung auf das Längenwachstum des Hypocotyls und auf die Anthocyanbildung bei Keimlingen von *Sinapsis alba* L. (*Brassica alba* Boiss.), *Planta*, 1957, **49**, 389.

PRINGSHEIM, E. G., Pure Cultures of Algae, Cambridge University Press, 1946, 41.

SHIBATA, K., BENSON, A. A., and CALVIN, M., The absorption spectra of suspensions of living micro-organisms, *Biochim. et Biophysica Acta*, 1954, **15**, 461.

STRAIN, H. H., MANNING, W. M., and HARDIN, G., Xanthophylls and carotenes of diatoms, brown algae, dinoflagellates and sea anemones, *Biol. Bull.*, 1944, **86**, 169.

SWEENEY, B. M., and HASTINGS, J. W., Characteristics of the diurnal rhythm of luminescence in *Gonyaulax polyedra*, *J. Cell. and Comp. Physiol.*, 1957, **49**, 115.

VAN DER KERK, G. J. M., Onderzoekingen over de bioluminescentie der lichtbacterien, Thesis, Utrecht, 1952.

Arch. int. pharmacodyn., 1959, CXXIII, No 1-2.

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VENOM OF THE STONEFISH SYNANCEJA HORRIDA (LINNAEUS) (¹), (²), (³)

BY

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(Received for publication 22-1-1959*).*

Stonefishes of the genus *Synanceja*, which inhabit shallow water over wide areas of the tropical Indo-Pacific, have caused a number of human deaths through stings by the venomous spines (HALSTEAD *et al.*, 1956; SMITH, 1957). Excruciating pain appears almost immediately at the site of the sting, and then spreads from the wound to the entire extremity. Ischemia and edema soon follow, and complete recovery from the local effects may be delayed for days or weeks. Systemic effects include weakness, sweating, respiratory distress and convulsions; death may occur within a few hours (HALSTEAD *et al.*, 1956; SMITH, 1951, 1957). The gross behavior of several species of animals injected with venom of the stonefish has been described (DUHIG and JONES 1928*a*; GAIL and RAGEAU, 1956); in addition, a hemolytic action has been reported (DUHIG and JONES, 1928*b*; DUHIG, 1929). No data are available on the nature of the systemic affects of the venom, or on the properties of the active substance(s), except for a recent report on the venom of *Synanceja verrucosa* Bloch and Schneider (SAUNDERS, 1959).

(¹) This paper represents results of research carried out by the University of Southern California under contract with the Office of Naval Research. Reproduction in whole or in part is permitted for any purpose of the United States Government. This study was supported also by the San Diego County Heart Association.

(²) A preliminary report of this work appeared in *Fed. Proc.*, 1958, *17*, 408.

(³) Contribution from the Scripps Institution of Oceanography, New Series. 1132

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A considerable number of specimens of *Synanceja horrida* (Linnaeus) have been collected, and some pharmacological and other properties of fresh and stored preparations of the venom are described in the present report.

MATERIALS AND METHODS

Collection of specimens. Specimens (¹) were collected at depths of about 15 feet or less near islands lying within about 15 miles of Singapore in a southerly direction, under the general supervision of Mr. A. FRASER-BRUNNER, Curator of the Van Kleef Aquarium, Singapore. The fish were maintained alive in the aquarium until used. A total of 24 specimens (mean standard length, 15 cm) were used in the work reported here.

Preparation of venom extracts. Live fish were removed from the aquarium tank and kept out of water in an ice-box at about 3° C for approximately one-half hour; this procedure rendered the fish quite inactive and facilitated the safe performance of the next step. The interspinous membranes were cut and each of the 13 dorsal spines cut free at the base. All subsequent manipulations were conducted at 5° C or less. The integumentary sheath was removed from each spine by stripping it off from the base in 2 pieces (care was exercised to avoid expressing venom from the underlying sacs). The pale blue-green spines with 2 attached venom sacs were thus revealed (HALSTEAD *et al.*, 1956). The venom sacs were slit open under 0.9 % NaCl solution; 1.0 ml of saline was used per g of spines (weighed prior to removal of the integumentary sheaths), and the fluid venom thus diluted. The extract was centrifuged at about 500 × *g* for 5 minutes, the insoluble fraction was re-extracted for 5 minutes with an additional 0.5 ml saline per g of spine, and this second extract was centrifuged. The supernatant fluid was decanted from a very small amount of insoluble material and combined with the first supernatant fluid to give a clear, colorless solution (pH approximately 6.8), which was stored at 3° C prior to preservation of activity by other procedures (see RESULTS).

Bioassay in mice. Extracts prepared as described above were diluted (usually 1 : 50) with 0.9 % NaCl solution immediately prior to bioassay, and injected into a tail vein of male albino mice (mean weight 20 g).

(¹) Specimens were identified as *Synanceja horrida* (Linnaeus) by Mr. FRASER-BRUNNER, and by Dr. D. W. STRASBURG, Pacific Oceanic Fishery Investigations, U.S. Fish and Wildlife Service, Honolulu, Hawaii. Their assistance is gratefully acknowledged.

The solution was injected over a period of about 5 seconds, and the volumes injected did not exceed 0.2 ml. All animals were observed over a minimum of 48 hours after injection.

Measurement of blood pressure and respiratory rate and recording of electrocardiogram in anesthetized rabbits. Albino rabbits (mean weight 2 kg) were anesthetized with 1-1.5 g/kg of urethan administered intraperitoneally. Blood pressure was recorded from a carotid artery with a mercury manometer, and respiration recorded by means of a thread sewn to the skin above the diaphragm and attached to a lever. The trachea was cannulated in all but 3 of the experiments; in some experiments artificial respiration by means of a pulmotor valve attached to a compressed air source was applied after the appearance of respiratory arrest. Venom solutions were injected intravenously through a catheter into a jugular vein. Electrocardiograms were taken at a chart speed of 25 mm/sec (1 mV equal to 10 mm); changes were most definite in Lead I, although Lead III was used in some experiments.

Chemical methods. Nitrogen was determined by the micro-Kjeldahl method (STEYERMARK, 1951). Protein was determined with the biuret reagent of GORNALL *et al.* (1949); a calibration curve was prepared with crystalline bovine albumin (Armour) over the range 0.5 to 2.0 mg of protein and the samples were read at 540 mμ on a Bausch and Lomb Spectronic 20 colorimeter.

RESULTS

Acute toxicity in mice. Intravenous injection killed animals in about 30 seconds to 30 minutes, depending on the dose; mice that did not die within a half-hour usually survived indefinitely with no apparent ill-effects. Amounts of venom fatal within 2-5 minutes produced any or all of the following initial symptoms: ataxia, circling movements, and partial or complete paralysis of the limbs. A period of inactivity usually followed, after which violent rolling or peddling movements occurred for about 15 seconds prior to respiratory arrest and death. The auricles and ventricles were almost always still contracting when the chest was opened about 1 minute after respiratory arrest; the auricles usually still displayed a regular rhythm. The mean LD_{50} determined for 5 separate extracts prepared from a total of 12 fish was 180 μg of protein/kg. Other extracts were assayed only approximately in 10 mice each, and the potencies were of the same order of magnitude. Approximately 3000 LD_{50} doses for mice were present in extracts prepared from all dorsal spines of each individual fish.

Intraperitoneal injection of venom extracts in volumes up to 0.15 ml produced death in from 30 minutes to 6 hours at the dosage levels investigated. The animals became very inactive within a few minutes after the injection, and displayed a markedly ataxic slow gait when prodded to move, which persisted until death. The respiratory rate usually slowed considerably for about an hour prior to death in those animals which died in several hours or more. Respiratory arrest and death were often preceded for a few minutes by intermittent convulsive movements. The LD_{50} following intraperitoneal administration (48 hour observation period) was approximately 10 times that following intravenous administration. Mice administered sublethal doses became inactive for about 4 hours but recovered.

Stability of venom under various conditions of storage. Extracts prepared as described above and stored at 3° C lost an average of one-fourth of their activity in 24 hours. Several procedures were used for preservation of the activity for shipment of the extracts and subsequent storage.

Extracts were bioassayed in mice within one hour after removing the spines from the fish, the pH adjusted to 7.5, and then preserved either (*a*) by addition of glycerol (analytical reagent) to a final concentration of 40 % or (*b*) by lyophilization. The glycerol-treated samples were stored subsequently in sealed glass vials in the presence of air, and the lyophilized samples in sealed glass vials *in vacuo*. After being maintained for up to 2 weeks at —15° C, the samples were packed in Dry Ice for 10 days while being transported from Singapore to the United States; subsequent storage has been at —20° C. Bioassays of representative glycerol-treated and lyophilized samples after about 1 year of storage has indicated that 50 to 100 % of the original potency has been retained. Precise determination of the stability on storage was not possible, because of differences in conditions under which bioassays were performed in Singapore and in the United States (*e.g.*, strains of mice used, environmental temperature and food). However, the symptoms produced in mice with samples which had been stored up to 1 year appeared identical with those evoked by freshly prepared extracts, and it is apparent that no marked deterioration of the samples occurred on storage.

Stability of the venom on storage of the spines themselves was also investigated. Spines removed from fish as described under MATERIALS AND METHODS were sealed in polyethylene bags, which were then packed in

Dry Ice for approximately 1 week and subsequently stored at —20° C. Extracts prepared from these spines in the usual manner after storage for periods up to 10 months were of comparable potency and produced in mice symptoms identical with those evoked by extracts prepared from fresh spines.

Other properties of venom. The undiluted venom, drawn from the venom sacs with a hypodermic needle, was a somewhat viscous clear colorless fluid. The pH was estimated with Hydrion paper to be 6.8-7.0.

Comparative bioassays of freshly-prepared extracts which had been dialyzed at 2° C for approximately 18 hours in Visking cellulose casing and of undialyzed controls indicated that none of the activity was lost on dialysis.

The bulk of the material lethal to mice was precipitated when the venom sacs were opened under deionized water rather than under 0.9 % NaCl solution. The copious white precipitate that formed immediately was separated from a clear colorless supernatant fluid by centrifugation. Bioassay of the supernatant fluid indicated that less than one-tenth of the usual activity was present. The insoluble fraction was then extracted with the same volume of 0.9 % NaCl solution, and nearly the entire precipitate dissolved almost immediately. The extract was then centrifuged and the supernatant fluid decanted from a very small amount of insoluble material. Bioassay of the supernatant fraction indicated a potency of the same order of magnitude as that obtained when extraction was carried out initially with 0.9 % NaCl solution.

Extracts prepared with 0.9 % NaCl solution as described under MATERIALS AND METHODS possessed a mean protein content (biuret) of 0.30 % and a mean nitrogen content of 0.046 %, which suggests that the bulk of the nitrogen in the extracts was present in the form of protein (although peptides might also be present).

Acute toxicity in unanaesthetized rabbits. Extracts which had been stored as described above in 40 % glycerol for about 6 months were injected into the marginal ear vein of 10 rabbits. Nystagmus appeared frequently within less than a minute after fatal or near-fatal doses and persisted for about 15 seconds. Injection of fatal doses produced a brief ataxia, followed by apparent paralysis of limb and neck musculature; convulsive movements occurred for a few seconds immediately prior to respiratory arrest and death. If they did not die within about 5 minutes the animals usually survived indefinitely without apparent ill-effects. The mean lethal dose/kg was approximately one-tenth the LD_{50} (intravenous) for mice.

Effects on blood pressure, respiratory rate and electrocardiogram of anesthetized rabbits. In these experiments identical results were obtained with glycerol-treated and lyophilized extracts; the extracts had been stored from 4 to 12 months after preparation from fresh fish. The initial doses used in about half of the experiments were without effect, and it was therefore possible to observe threshold effects with subsequent doses in these animals. There was no evidence of a cumulative effect or tachyphylaxis following repeated injection of small to moderate doses at intervals of about 20 minutes. Sixteen rabbits were used in these experiments.

Minimal doses produced a slight fall in blood pressure accompanied by an increase in respiratory rate, with no effect upon the heart rate or electrocardiogram (FIG. 1); these effects disappeared within 5 to 10 minutes. The observation that the respiratory rate sometimes increased markedly with minimal (15 % or less) decrease in blood pressure suggests that the respiratory stimulation was in part at least an independent action of the venom and not merely a reflex response to the hypotension. Larger doses caused a marked fall in blood pressure and increase in respiratory rate, with evidence of myocardial ischemia or injury (occasional flattening or inversion of T wave, and a consistent displacement

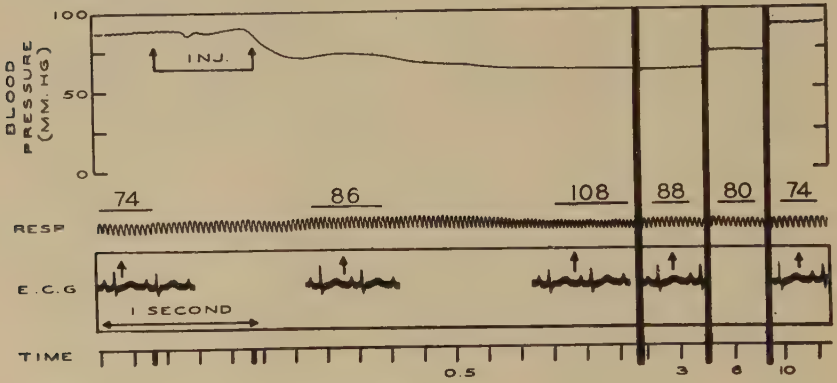

FIG. 1

Effect of small dose of venom of *Synanceja horrida* on blood pressure, respiration, and electrocardiogram of a rabbit. 8 μg of venom protein/kg was injected between arrows above. Heavy vertical lines indicate interruption of recording. Numbers above record of respiration indicate respiratory rate/min during time interval denoted by horizontal lines beneath these numbers. Signal marks are at 5 second intervals, and numbers below signal marks show time (min) after injection of venom. Arrows above ECG record (Lead I) denote point at which record taken; time scale for ECG is indicated by horizontal arrow. Inspiration appears as downward stroke on record of respiration.

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of the S-T segment); the cardiac rate changed little or not at all, and these effects disappeared within about 10 minutes (FIG. 2). The blood pressure often returned, especially after the first dose administered to a given animal, to a value 10 to 30 % above the pre-injection pressure,

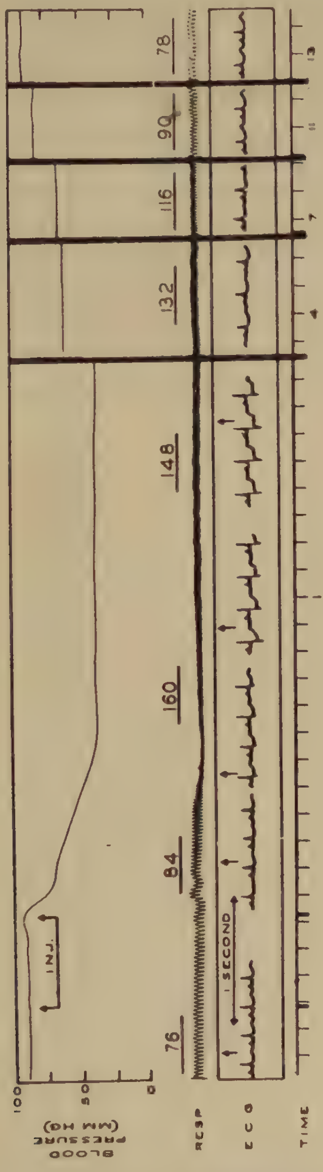

FIG. 2

Effect of moderate dose of venom of *Synanceja horrida* on blood pressure, respiration, and electrocardiogram of a rabbit. 11.5 µg of venom protein/kg was injected between arrows above. Heavy vertical lines indicate interruption of recording. Numbers above record of respiration indicate respiratory rate/min during time interval denoted by horizontal lines beneath these numbers. Signal marks are at 5 second intervals, and numbers below signal marks show time (min) after injection of venom. Arrows above ECG record (Lead I) denote point at which record taken; time scale for ECG is indicated by horizontal arrow. Inspiration appears as downward stroke on record of respiration.

and this elevated pressure usually persisted for a half-hour or longer. Injection of fatal doses produced effects as described above initially; a variety of additional electrocardiographic changes appeared as the blood pressure continued to decrease (*e.g.*, occasional premature auricular and ventricular impulses, first degree AV block, ventricular tachy-

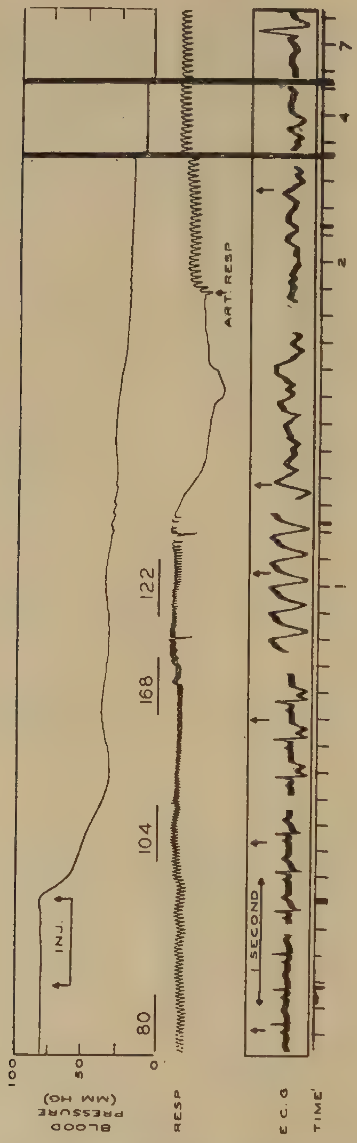

Fig. 3

Effect of fatal dose of venom of *Synanceja horrida* on blood pressure, respiration, and electrocardiogram of a rabbit. 13 μg of venom protein/kg was injected between arrows above. Artificial respiration started at arrow at rate of 56/min. Legend otherwise as in figure 2 above.

cardia, ventricular fibrillation). The latter arrhythmia occurred in about one-half of the animals following injection of fatal doses. The respiration slowed and finally ceased and the blood pressure continued to decrease (FIG. 3). The auricles (and sometimes the ventricles) were usually still beating when the chest was opened within a minute or two of respiratory arrest; some irregular electrical activity persisted in the heart for approximately 5 minutes longer.

Artificial respiration initiated in 7 animals within about one-half minute after respiratory arrest was ineffective. In one animal spontaneous respiration returned about a minute after respiratory arrest, without the use of artificial respiration; blood pressure and electrocardiogram soon returned to the control values, and recovery from the effects of the venom was apparently complete within 10 minutes.

The mean lethal dose in the above experiments was approximately 15 μg of protein per kg.

DISCUSSION

Adequate medical histories of fatal stings from "stonefish" unfortunately are not available, but it is clear from a number of fragmentary accounts (HALSTEAD *et al.*, 1956; SMITH, 1957) that profound systemic effects of an undefined nature may lead to "collapse" and death within a short time. The actual cause of death is not apparent from these accounts. The work reported here indicates that the primary action of the venom on the cardiovascular system is the production of a marked hypotension (together with an increased respiratory rate), with essentially no change in cardiac rate or electrocardiogram following small doses. Amounts of venom sufficient to lower the blood pressure to about one-half the pre-injection value produced also evidence of myocardial injury which was reversible if the animal recovered; cardiac rate changes were again minimal, but this of course may have been due to depression of cardiac reflexes by anesthesia. We have no evidence at present to indicate whether these effects on the electrocardiogram were due to a direct action on the myocardium or coronary vessels, or were secondary to the hypotension. However, in accord with the latter explanation, a marked fall in blood pressure always preceded displacement of the S-T segment, and return of the blood pressure to normal coincided with reversal of the electrocardiographic changes. Hyperventilation may also be associated with changes in the T wave and occasionally in the S-T segment (THOMPSON, 1943); we found, however, that the electrocardiographic effects of non-fatal doses of venom coincided more closely in time and degree with changes in blood pressure than with the increase in respiratory rate.

Respiration was arrested as a terminal event, but artificial respiration was ineffective in prolonging the life of the animal (although one recovered spontaneously after respiratory arrest of about a minute). Therapeutic measures directed toward the support of the circulation would appear to be indicated in the treatment of seriously poisoned victims, together with artifical respiration if needed. Experiments designed to evaluate the effectiveness of pressor agents are in progress.

The pharmacological actions of the venom of *Synanceja horrida* (Linnaeus) on mice and rabbits appear to be essentially identical to those described previously in less detail for *Synanceja verrucosa* Bloch and Schneider (Saunders, 1959). Furthermore, in both species the substance(s) responsible for the biological activity in mice were non-dialyzable. This fact, together with the finding that substantial amounts of protein were present in both venoms, suggests that the active material is identical with or closely associated with protein.

Summary

Extracts have been prepared from the venomous dorsal spines of the " stonefish " *Synanceja horrida* (Linnaeus), and the pharmacological actions of these extracts investigated in mice and rabbits.

Intravenous injection into mice produced death in less than a minute or up to about one-half hour; symptoms produced included ataxia, partial or complete paralysis of the limbs, rolling and peddling movements, and respiratory arrest. The primary action in anesthetized rabbits was a fall in blood pressure, accompanied by increase in respiratory rate; with larger doses there was evidence of myocardial injury (displacement of S-T segment). After injection of fatal doses the blood pressure fell to zero, with marked electrocardiographic changes (*e.g.*, ventricular tachycardia and fibrillation, and other arrhythmias); respiration was arrested as the blood pressure continued to decrease but artificial respiration did not prolong the life of the animal.

The venom contained considerable quantities of protein, and the active material was non-dialyzable, suggesting that a protein or mixture of proteins was responsible for the lethal action. Extracts prepared in 0.9 % NaCl solution retained substantial activity after lyophilization or after addition of glycerol to a final concentration of 40 %, even after

subsequent storage for one year at —20° C. Extracts prepared from spines that had been stored for nearly a year at —20° C had essentially the same potency as those prepared from fresh fish.

The mean LD_{50} of freshly prepared extracts following intravenous injection into mice was 180 μg of protein per kg, and the mean lethal dose in anesthetized rabbits was approximately 15 μg of protein per kg.

S. WIENER (*Med. J. Aust.*, 1958, *2*, 219) has recently reported additional cases of stonefish sting and discussed methods of treatment.

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REFERENCES

DUHIG, J. V. and JONES, G. *Mem. Qd. Mus.*, 1928*a*, *9*, 136.
DUHIG, J. V. and JONES, G. *Aust. J. exp. Biol. med. Sci.*, 1928*b*, *5*, 173.
DUHIG, J. V. *Z. Immunitätsforsch.*, 1929, *82*, 185.
GAIL, R. and RAGEAU, J. *Bull. Soc. Pat. exot.*, 1956, *49*, 846.
GORNALL, A. G., BARDAWILL, C. J. and DAVID, M. M. *J. biol. Chem.*, 1949, *177*, 751.
HALSTEAD, B. W., CHITWOOD, M. J. and MODGLIN, F. R. *Trans. Amer. micr. Soc.*, 1956, *75*, 381.
SAUNDERS, P. R. *Science*, 1959, *129*, 272.
SMITH, J. L. B. *Copeia*, 1951, 207.
SMITH, J. L. B. *Copeia*, 1957, 249.
STEYERMARK, A. Quantitative Organic Microanalysis, Blakiston, New York, 1951.
THOMPSON, W. P. *Amer. Heart J.*, 1943, *25*, 372.

(1028)

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BIBLIOGRAPHY, CARTOGRAPHY, DISCOVERY, AND EXPLORATION OF THE ISLAS REVILLAGIGEDO[1]

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INTRODUCTION

This paper was prepared with four principal objectives: to compile a bibliography of references to the Islas Revillagigedo, to publish new charts of Isla San Benedicto and Isla Socorro which have been made from recent aerial photographs, to attempt to standardize spelling and location of geographic names, and to include an account of the discovery and exploration of the archipelago. Original maps, charts, and references to the nomenclature of the islands have been consulted in so far as possible.

We gratefully acknowledge the help of the late Mr. Joseph R. Slevin, California Academy of Sciences, for information used in compiling table 2. Dr. Carl Fries, Jr., previously with the U.S. Geological Survey, assisted in the selection of the most suitable geographic names; he also translated many of these names from English to Spanish. Dr. Meredith F. Burrill, Director of the U.S. Board on Geographic Names, recommended names of features on Isla Socorro which were obtained from Mexican sources. The U. S. Navy Hydrographic Office and British Admiralty furnished photocopies of original charts, sketch surveys, and publications. We also are indebted to the many other persons who have assisted us in the search for bibliographic material, furnished information on visits to the Islas Revillagigedo, read preliminary copies of the manuscript, and offered suggestions. Mr. Robert C. Winsett of the Scripps Institution of Oceanography drafted the charts illustrated in this paper.

CARTOGRAPHY AND NOMENCLATURE

The early evolution of the names and geographic locations of the four Islas Revillagigedo, as shown on charts prior to 1800, has been treated by Wagner (1937) and briefly mentioned in another section of this paper and will not be discussed further.

In 1793 Captain James Colnett, R.N., made the first detailed chart of Isla San Benedicto (Isle St. Berto)[3], Isla Socorro (Socoro), and Roca Partida (Roka Partida). His "Plan of the Islands of Revillagigedo" was published by the London firm of A. Arrowsmith in January, 1798, and a copy of the chart accompanies Colnett's book (1798). Captain Sir Edward Belcher, C.B., R.N., made sketch maps of Isla Clarión and Bahía Braithwaite on Socorro in 1839 (however, 1840, the year after the end of his voyage, is the date given on his original chart)[4]. The sketch maps made by Colnett and Belcher were incorporated into British Admiralty Chart no. 1936 (no title) which was first published in June, 1849.

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[3] Apparently there is no saint of this name (Pablo G. Franco, personal communication).

[4] Photographic copies of the original Hydrographic Office and British Admiralty charts and the sketch surveys by Belcher and Dewey have been examined by the authors.

The best published charts of the islands were the result of surveys made by Commander George Dewey, U.S.N., and his officers in 1874. These sketch surveys were used in the first edition of the U. S. Navy Hydrographic Office[5] Chart no. 1687, "Islands of the Revilla Gigedo Group and Alijos Rocks" (exclusive of Isla Clarión), which was published in January, 1898. A separate chart, no. 1688, of only Isla Clarión was published in February, 1898. About this time the British Admiralty also began to use the U. S. Charts in revised editions of Chart no. 1936, "Islands of the North Pacific Ocean." Of the Islas Revillagigedo only Belcher's sketch of Bahía Braithwaite was retained from the first edition. The H.O. combined all of the islands of the archipelago into one chart in June, 1951, when the ninth edition of Chart no. 1688, "Islas Revilla Gigedo, Guadalupe and Escollos Alijos," was published.

The Islas Revillagigedo were visited by the Mexican Transporte de Guerra *Oaxaca* in 1899. Sketch maps, made by Subteniente Arturo Puga and Segundo Teniente José Servín y L., appear to have been first published by Muñoz Lumbier (1919). The sketches are profile views, except for an excellent plan of Bahía Sulphur which is complete with soundings. Muñoz Lumbier's plate 3, "Isla de Clarión," from the *Oaxaca* survey shows Pico Tienda de Campaña (Tent Peak) to be higher than Monte Gallegos (Mt. Gallegos). Monte Gallegos is shown as the higher peak on the H.O. and British Admiralty charts. Although Pico Tienda de Campaña appears to be higher from a ship at sea Wilfred B. Bryan, Jr., (personal communication), who has climbed both peaks, reports that it is difficult to judge which is the higher on land.

A number of photographic flights to Isla San Benedicto and Isla Socorro, which have resulted in more accurate charts of these two islands (figures 1 and 2), were made by airplanes of the U.S. Navy between 1952 and 1956 at the request of the University of California, Scripps Institution of Oceanography. Figure 1 was drawn from an uncontrolled two-photograph mosaic of San Benedicto. The scale was determined by photogrammetric methods and is considered to be reliable. Figure 2 of Isla Socorro also was drawn from an uncontrolled mosaic, consisting of numerous vertical photographs taken on two different flights and adjusted to a common approximate scale, supplemented with aerial oblique photographs. No control has been established in the field. Because of the large natural scale of the mosaic, absence of rectification of the individual aerial photographs, and altitude of Cerro

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[5] Subsequently abbreviated H.O.

Evermann, the chart scale and positions of geographic features should be considered as only approximate.

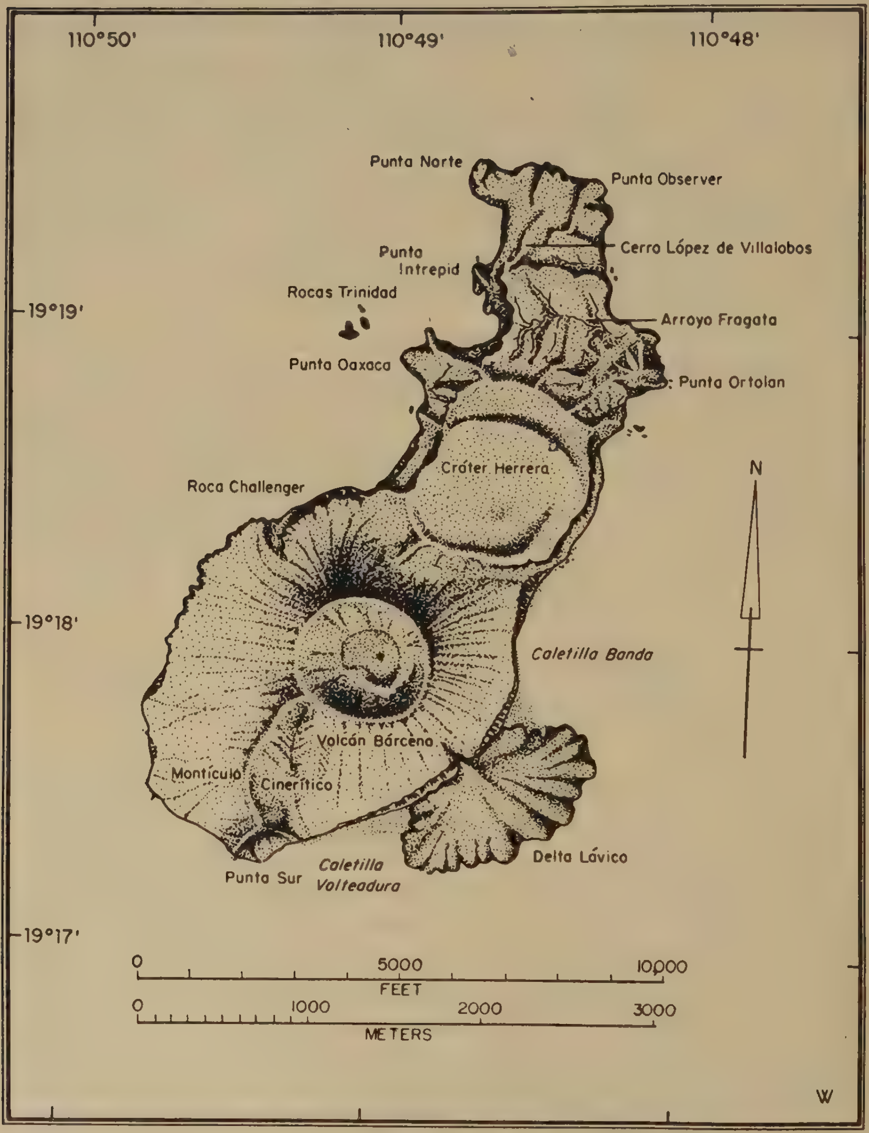
110°50'
110°49'
110°48'
19°19'
19°18'
19°17'
Punta Norte
Punta Observer
Cerro López de Villalobos
Punta Intrepid
Rocas Trinidad
Arroyo Fragata
Punta Oaxaca
Punta Ortolan
Cráter Herrera
Roca Challenger
N
Caletilla Banda
Volcán Bárcena
Montículo Cinerítico
Delta Lávico
Punta Sur
Caletilla Volteadura
0
5000
10000
FEET
0
1000
2000
3000
METERS
W

Figure 1. Map of Isla San Benedicto.

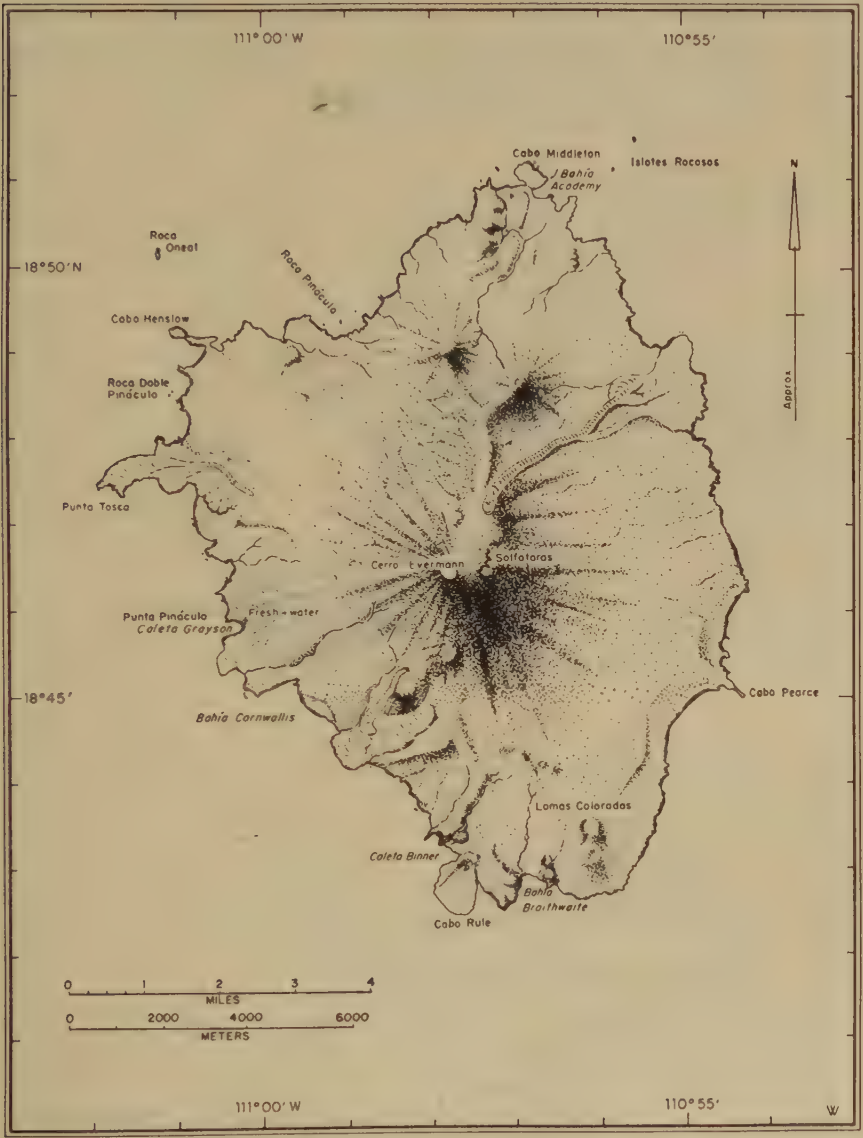
111° 00' W
110°55'
Cabo Middleton
Islotes Rocosos
Bahía Academy
N
Roca Oneal
Roca Pináculo
18°50'N
Cabo Henslow
Roca Doble Pináculo
Approx
Punta Tosca
Solfataros
Cerro Evermann
Punta Pináculo
Fresh-water
Caleta Grayson
18°45'
Cabo Pearce
Bahía Cornwallis
Lomas Coloradas
Caleta Binner
Bahía Braithwaite
Cabo Rule
0
1
2
3
4
MILES
0
2000
4000
6000
METERS
111°00' W
110°55'
W

Figure 2. Map of Isla Socorro.

Figure 3, a sketch map of Isla Roca Partida, was prepared from H.O. Chart no. 1688 modified by a study of photographs taken at sea from the R/V *Paolina-T* in 1953.

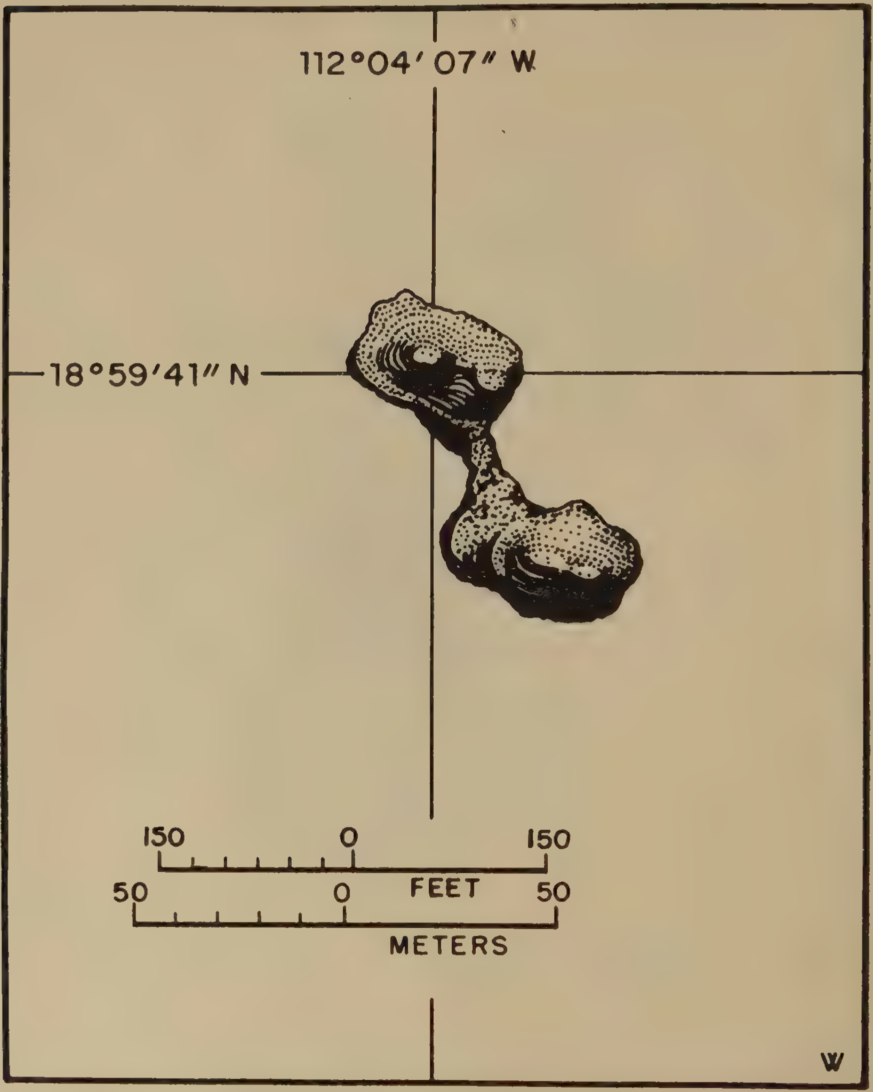
112°04′07″ W
18°59′41″ N
150
0
150
FEET
50
0
50
METERS
W

Figure 3. Sketch map of Isla Roca Partida.

(1034)

The map of Isla Clarión, figure 4, which is the least well delineated island of the group, was drawn from H.O. Chart no. 1688 with changes made from photographs taken on land from the sea during the visits of the R/V *Paolina-T* in March, 1953, and the R/V *Crest* in May, 1955. In May, 1955, a number of gyrocompass bearings and radar positions of Isla Clarión were made from the R/V *Crest* by one of the authors (Richards). These new data, which should help to place geographic features more accurately, unfortunately have not yet been worked up.

In table 1 the place names proposed for Isla San Benedicto were necessitated in order to describe the new volcano and the geology of the island. The two pre-existing names also have been included for completeness.

The new map of Isla Socorro, figure 2, in many ways more nearly resembles Colnett's 1793 sketch than it does the H.O. Chart no. 1688. Names that Colnett appears to have given to certain geographic features are shown for other features on the H.O. chart. Table 2 compares the names used by Colnett and the H.O. Caleta Binner was originally called Binmers Cove by Colnett in honor of his kinsman ". . . Mr. Binmer, first assistant surveyor of the Navy, who had superintended the original construction of the sloop *(Rattler)* . . . ," Colnett (1798, p. xii). The name is correctly spelled on the 1798 Arrowsmith chart, but is incorrect on both the original and present H.O. and British Admiralty charts. Despite the fact that Colnett's names have priority, "Binner" and the H.O. names have been retained in figure 2 because they have been in use in the literature for over 150 years. The location of Bahía Cornwallis in figure 2 has been clarified; the bay was unrecognizable on the H.O. chart.

Colnett's name, "Pinnacle Point" (Punta Pináculo), is proposed for the headland with the prominent offshore stack at the northwest entrance to Caleta Grayson (Grayson's Cove). This name was selected following the recommendation by Dr. Raymond M. Gilmore, U.S. Fish and Wildlife Service, that Caleta Grayson should be better identified because of the importance of the cove; it is the only permanent source of flowing fresh water in the entire archipelago. Punta Pináculo and the trees behind the beach identify Caleta Grayson from the sea.

An unnamed bay southeast of Cabo Middleton was visited on the November, 1953, Scripps expedition. In order to identify collections made in this locality, the name "Bahía Academy" (Academy Bay), was proposed by Richards (unpublished manuscript) in recognition of the 1925 California Academy of Sciences expedition to the Islas Revillagigedo.

A suggested translation of Red Hills, which are located on the southeast side of Socorro (Hanna, 1926, p. 50), is Lomas Coloradas. Two isolated rocky sea stacks are located northeast of Cabo Middleton. The name Rock

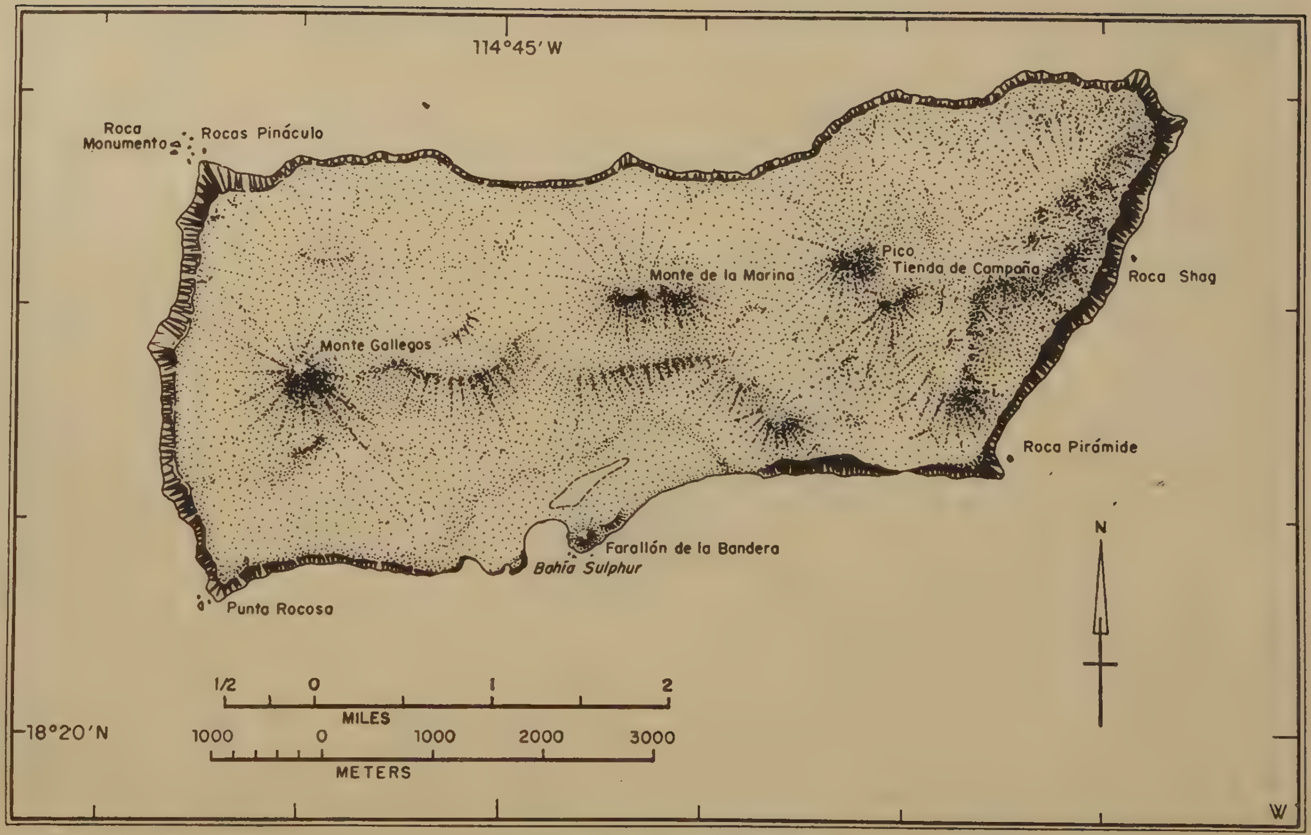
114°45′ W
18°20′ N
Roca Monumento
Rocas Pináculo
Monte Gallegos
Monte de la Marina
Pico
Tienda de Campaña
Roca Shag
Roca Pirámide
Farallón de la Bandera
Bahía Sulphur
Punta Rocosa
N
W
1/2
0
1
2
MILES
1000
0
1000
2000
3000
METERS

Figure 4. Sketch map of Isla Clarión.

(1036)

Islets, which has been used for these stacks (H.O. Chart no. 1688, 1951), is translated to Islotes Rocosos in figure 2.

The following two names used on H.O. Chart no. 1688 of Isla Socorro were not found on Mexican charts or references (Meredith F. Burrill, personal communication): "Old Man of the Rocks Point" (southwest headland of Caleta Grayson) and "Table Range" (plateau area on east Socorro). We recommend that these names be deleted.

On Isla Clarión, Bahía Sulphur has not been translated "Bahía Azufre," as shown on certain charts, because the bay was named after the H.M.S. *Sulphur*. On Belcher's original chart of the Bahía Sulphur area this name was applied to the bay west of Farallón de la Bandera. The bight east of Farallón de la Bandera is unnamed. Shag Rock at the east end of Clarión was called "Roca del Cuervo" (Crow Rock) by the Escuela Superior de Guerra (Vivó, 1949, p. 59). The original name is retained.

With the exception of the names given above and in table 1, all names used in figures 1 to 4 have appeared in one or more of the following references: Atlas Geográfico de la Estados Unidos Mexicanos (1946); British Admiralty Chart no. 1936 (1952 edition with small corrections to 1954); Carta de la República Mexicana (1949, Comité Coordinator del Levantamiento de la República Mexicana, Tacumbaya, D.F.); Colnett (1798); Derrotero de las Costas de la República Mexicana (1939); Escuela Superior de Guerra (1949); Muñoz Lumbier (1919); U.S. Board on Geographic Names (1952); and U.S. Navy Hydrographic Office Publication no. 56 (1874, first edition—written by Dewey), Chart no. 1688 (1951, 9th edition) and no. 1687 (1925, 9th edition).

Table 3 lists distances in nautical miles between the islands and cities or geographic features in Baja California, California (U.S.A.) Colima, and Jalisco.

TABLE 1

Proposed and Existing Nomenclature of Isla San Benedicto

Name	*Location and Notes*
Punta Sur (South Point)	Suggested name for the southwest point of the island; it has been used previously by Toscano (1940, p. 322). Extreme southern point of the pre-eruption island, H. O. Chart no. 1688.
Montículo Cinerítico (Ash Heap)	Translation of the existing name for the eroded volcanic ash cone on south San Benedicto which was named in 1925 by the California Academy of Sciences (Hanna, 1926, pp. 20, 63). The maximum altitude, determined by photogrammetric methods, is about 310 meters. ("Black Bluff," shown on H. O.

Table 1 *(Continued)*

Proposed and Existing Nomenclature of Isla San Benedicto

Name	*Location and Notes*
	Chart no. 1688—1951, 9th edition—on the east side of the Ash Heap, has been completely buried under Volcán Bárcena. The "White Bluffs" on the southern end of the pre-eruption island no longer exist.)
Caletilla Volteadura (Turnover Bight)	Suggested name for the newly created small open bay or bight on the southern end of the island between Punta Sur and the new lava flow (Delta Lávico). The name is derived from an incident in December, 1952; the skiff completely overturned when making a landing in this locality.
Volcán Bárcena (Bárcena Volcano)	Name suggested in 1953 by the late Ing. Teodoro Flores, Director of the Instituto de Geología in the Universidad Nacional de México, in honor of the Mexican geologist Mariano Bárcena (1842–1899). Volcán Bárcena replaces the previous unofficial name of Boquerón, meaning Big Mouth, which was suggested by Howel Williams and proposed by Dietz (1953). The maximum altitude, determined by photogrammetric methods, is about 340 meters.
Delta Lávico (Lava Delta)	Suggested name for the new lava flow from Volcán Bárcena which formed between December, 1952, and March, 1953.
Caletilla Banda (Banda Bight)	Suggested name for the newly created small open bay, or bight, on the east side of the island between the Delta Lávico and Cráter Herrera. It is named in honor of Longinos Banda who was in charge of the first party to land on the island. See Banda (1862).
Cráter Herrera (Herrera Crater)	Translation of the existing name for the old crater in the central part of the island. It was named by the California Academy of Sciences in 1925 in honor of Prof. Alphonso Herrera (Hanna, 1926, pp. 20, 63).
Punta Ortolan (Point Ortolan)	Suggested name for the southern promontory of the headland on northeast San Benedicto between Cráter Herrera and the extreme northeastern cape (Cabo Observor). It is named after the U.S.S. *Ortolan*, the ship which carried the 1925 California Academy of Sciences expedition to the Islas Revillagigedo.
Arroyo Fragata (Frigate Arroyo)	Suggested name for the dry main channel of the largest drainage system between Cráter Herrera and the northern peak (Cerro López de Villalobos). In November, 1953, the only frigate, or man-of-war bird, rookery on the island was located north of the arroyo on the eastern side of the island. See Brattstrom and Howell (1956).

TABLE 1 *(Continued)*

Proposed and Existing Nomenclature of Isla San Benedicto

Name	*Location and Notes*
Cerro López de Villalobos	Suggested name for the fourth highest topographic feature on the island. The volcanic hill is named in honor of Ruy López de Villalobos who discovered Isla San Benedicto in 1542. The maximum altitude, determined by photogrammetric methods, is about 225 meters.
Punta Observer (Observer Point)	Suggested name for the northeast point. This point is named after the U. S. yacht *Observer* which brought the first party to land on the island after the birth of the volcano. The Delta Lávico was first observed from the vicinity of this point on December 9, 1952, by the scientific party, less than 20 hours after the lava had broken through the base of Volcán Bárcena.
Punta Norte (North Point)	Suggested name for the northwest point.
Punta Intrepid (Point Intrepid)	Suggested name for the first minor headland on the western side of the island south of the north end. The point is located west of Cerro López de Villalobos and is named after the U. S. tuna clipper M/V *Intrepid* which visited the island on August 12, 1952, and furnished a valuable first report of Volcán Bárcena after its birth.
Rocas Trinidad (Trinity Rocks)	Suggested name for the three stack islets located off the west side of the island.
Punta Oaxaca (Point Oaxaca)	Suggested name for the only major headland on the western side of the island. It is named after the Mexican transport *Oaxaca* which visited the islands in 1899. See Mitchell (1933, pp. 124–135).
Roca Challenger (Challenger Rock)	Suggested name for the volcanic dome west of Cráter Herrera. Except for a northwest facing cliff the dome is now buried under Volcán Bárcena. The rock is named after the U. S. tuna clipper M/V *Challenger*, the only witness to the birth of Volcán Bárcena on August 1, 1952. Photographs taken from the *Challenger* show the beginning eruption column ascending from behind this cliff or rock.

(1040)

TABLE 2

Variant Names on Isla Socorro

Location	*Name used on Colnett's 1798 Chart*	*Name Used on H.O. Chart No. 1688 (9th Edition, 1951)*[a]	*Name Used by Authors in Figure 2*
North headland	Cape Middleton	Cabo Middleton (Cape Middleton)	Cabo Middleton
Rock Islet off northwest headland	O Neals Rock	Oneal Rock (Oneal Rock)	Roca Oneal
Northwest headland	——	Cabo Henslow (Cape Henslow)	Cabo Henslow
West headland	Cape Henslow	Punta Tosca (Rugged Point)	Punta Tosca
Northwest headland of Caleta Grayson	Pinnacle Point	——	Punta Pináculo (Pinnacle Point)
Central southwest bay	Cornwallis Bay	——	Bahía Cornwallis (Cornwallis Bay)
South-southwest bight	——	Bahía Cornwallis (Cornwallis Bay)	——
Headland south of Bahia Cornwallis	Cape Rule	——	——
Small cove west of south headlands	Binmers Cove	Caleta Binners (Binners Cove)	Caleta Binner
Largest south headland	——	Cabo Regula (Cape Rule)	Cabo Rule
Bay east of south headlands	Braithwaite Bay	Bahía Braithwaite (Braithwaite Bay)	Bahía Braithwaite
East headland	——	Cabo Pearce (Cape Pearce)	Cabo Pearce
Northeast headland	Cape Pearce	——	——

[a] Name enclosed in parentheses from H.O. Chart no. 1687 (9th edition, May, 1925).

Table 3

Airline Distances in Nautical Miles[7]

	Isla Clarión	*Cabo Corrientes, Jalisco*	*Los Angeles, Calif.*	*Manzanillo, Colima*	*Isla Roca Partida*	*Isla San Benedicto*	*San Diego, Calif.*	*Cabo San Lucas, B.C.*	*Isla Socorro*
Isla Clarión	—	526	951	591	153	226	866	368	209
Isla Roca Partida	153	371	956	462	—	73	864	261	60
Isla San Benedicto	226	296	964	370	73	—	871	220	27
Isla Socorro	209	312	982	378	60	27	890	246	—

[7] Distances based on U. S. Navy Hydrographic Office Chart no. 1066 (66th edition, 1945) and unpublished charts by one of the writers (Richards).

DISCOVERY AND EXPLORATION

Probably the best description of the discovery of the Islas Revillagigedo has been compiled by Burney (1803, pp. 167–169, 226–232; 1806, pp. 348–350), who states that his references are accounts by Gaetan, Ramusio's Collection, (1613); May (Anon., 1621); Galvaom (1731); Herrera (date unknown); and Grijalva (date unknown). Isla Socorro was discovered in December, 1533, by Hernando de Grijalva, commander of the Spanish ship *San Lazaro,* who named the island Santo Tomás. According to Edward R. del Rip (quoted in Hanna, 1926, p. 51), Santo Tomás was named Socorro in 1608 by Captain Martín Yañez de Armida in honor of his wife.

In 1542 Ruy López de Villalobos, in command of a squadron of ships from New Spain, discovered two islands which he named Santo Tome and La Annublada. According to Burney (1803, p. 232), "The island first seen by Villalobos . . . is the same which is marked Sto. Berto, in some of the present charts. Villalobos supposed it to be the island which had been discovered by Grijalva, and therefore called it Sto. Tome. The second island, however, which he named La Annublada, and which has since been named Socorro, is evidently the Sto. Tomás of Grijalva." The common interpretation by historians is that López de Villalobos' Annublada (also spelled Anublada or A Nublada, meaning cloudy—nublado) was later called Santo Berto *(sic)* or San Benedicto. Burney's account appears to be more probable because Cerro Evermann on Socorro with an altitude of about 3500 feet above sea level is frequently cloud capped; consequently the designation "cloudy" is appropriate. Also, according to Galvaom's statements, which are given by Burney (1803, p. 228, see also p. 232), López de Villalobos' Anublada (Socorro) apparently was located south of his Santo Tomás (San Benedicto).

West of the two islands López de Villalobos discovered a divided rock which he called Roca Partida.

The discovery of Isla Clarión (originally named Santa Rosa by Joseph Camacho—date unknown), as well as Roca Partida, previously has been credited to Camacho (Mitchell, 1933, p. 119). However, from Burney (1806, pp. 348–350) it appears that Clarión was discovered in 1615 instead of 1779. Burney relates that in December 1615 Admiral Joris Spilbergen saw two islands (undoubtedly San Benedicto and Socorro) after sailing west-southwest from Cabo Corrientes on the coast of Mexico—28°21′ North latitude. The next day a third island was sighted which at first was mistaken for a ship (Roca Partida). Two days later at 18°20′ North a fourth island which had five hills was discovered; each hill appeared to be a separate island. Although Burney quoted the account of Spilbergen's voyage from an early reference,[8] he did not realize the significance of Spilbergen's fourth island. The sailing time to Clarión from Roca Partida (a distance of 153 nautical miles) as well as the latitude (18°21′ North) and the five hills could only describe Clarión which, from north or south of the Island, appears to be composed of three, five, or six peaks depending upon one's bearing and distance.

In 1793 Captain James Colnett (1798, pp. 116–117) named the archipelago "Revilla Gigedo"[9] in honor of the viceroy to New Spain, Don Juan Vicente de Güemes Pacheco de Padilla, the second Count Revillagigedo.

Table 4 lists known visits to the Islas Revillagigedo which resulted in new information on the islands.

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[8] Page 80 in Miroir, Oost and West Indical, Amsterdam, 1621: a French translation of an account of Admiral Spilbergen's Journal by Jan Cornelisz May, alias Mensch-eter, principal mariner or ship master according to Burney (1806, p. 330). However, Mr. G. A. Cox, Director of the Nederlandsch Historisch Scheepvaart Museum in Amsterdam, advises that May could not have written this book and that the author is unknown (personal communication).

[9] This undoubtedly was the unfortunate start of the double name ("Revilla Gigedo") usage for the islands by certain authors and cartographers. In 1952 the U. S. Board on Geographic Names (p. 6) adopted "Islas de Revillagigedo" (literally Islands of Revillagigedo) as the official name for United States of America Government use. The current geographical practice is generally to delete the "de" in cases such as this. The shortened form, "Islas Revillagigedo," is the name most commonly used by Mexican authors and has been adopted in this paper.

TABLE 4

Visits to the Islas Revillagigedo[10]

Year	*Ship*	*Islands Visited*	*Investigator*[11]	*Chief Collections, and/or Study*	*Notes and References*[12]
1533	*San Lazaro*	Socorro	Capt. Hernando de Grijalva	Exploration	Discovery of Isla Socorro. Burney (1803, pp. 167–169).
1542	not known	San Benedicto Roca Partida	Ruy López de Villalobos	Exploration	Discovery of Isla San Benedicto and Isla Roca Partida. Burney (1803, pp. 226–232).
1615	*Great Sun*	Clarión	Adm. Joris Spilbergen	Exploration	Discovery of Isla Clarión. Burney (1806, pp. 348–349) and this paper.
1793	*Rattler*	San Benedicto Socorro Roca Partida	Capt. James Colnett, R.N.	Natural history observations, soundings, charts	Archipelago named in honor of Count Revillagigedo. Colnett (1798, pp. 86–90, 107–120).
1825	*Boston*	Socorro	Capt. Benjamin Morrell, Jr.	Sealing	Morrell (1832, p. 213).
1837 and 1839	H.M.S. *Sulphur* and H.M.S. *Starling*	Socorro Clarión	Capt. Edward Belcher, R.N.	Zoology, botany	British naval exploring expedition. In 1837 Socorro was not visited and no landing was made on Clarión. Belcher (1843, pp. 48, 346–350).
1848	U.S.S. *Portsmouth*	Socorro	Lt. J. W. Revere, U.S.N.	Exploration	Noted an active eruption of Cerro Evermann. Revere (1947, pp. 234–235). For a discussion of this observation see Richards and Dietz (1956, p. 157).

[10] Although this table is principally concerned with scientific expeditions or visits, other known explorations are also included.

[11] Where more than three investigators participated in an expedition only the investigator in charge or the captain of the ship is listed.

[12] In most cases only the general account of each visit is listed.

(1044)

TABLE 4 *(Continued)*

Year	*Ship*	*Islands Visited*	*Investigator*[11]	*Chief Collections, and/or Study*	*Notes and References*[12]
1862	*Maria*	San Benedicto Socorro	Longinos Banda (in charge)	Geographical locations, geology, plants, animals	Sponsored by the State of Colima, Mexico. Banda (1862). Also reviewed in Mitchell (1933, pp. 118–126).
1865 1867	not known *Republicana*	Socorro	Andrew J. Grayson	Birds, physical geography, natural history	No published information has been found on the 1865 visit. Concerning the 1867 visit see Grayson (1872).
1868	*Joven Hortenza* and *India*	Socorro	Francisco Javier Cueva (in charge)	Exploration	According to Almada (1939, pp. 159) the *Joven Hortenza* took the party to Socorro and the *India* returned the group to the mainland. Formal Mexican possession of the islands resulted from this expedition (Almada, 1939, p. 159–160).
1869	not known	Socorro	John Smith (in charge)	Colonization	Origin of the sheep of Socorro. Hanna (1926, p. 52).
1874	U.S.S. *Narragansett*	San Benedicto Socorro Roca Partida Clarión	Cdr. George Dewey, U.S.N.	Insular sketch surveys	Sketch maps used on present day U.S. Hydrographic Office charts. Dewey (1874, pp. 58–60.)
1880	*Hassler*	Socorro Clarión	Lt. Cdr. H. E. Nichols, U.S.N.	Magnetic observations	Magnetic survey by the U.S. Coast and Geodetic Survey along the coasts of Mexico and Central America. Observed magnetic dip, declination, intensity, latitude and longitude. Report of the U.S. Coast and Geodetic Survey (1883, pp. 37–38) and Schott (1883, pp. 190–221).

TABLE 4 *(Continued)*

Year	*Ship*	*Islands Visited*	*Investigator*[11]	*Chief Collections, and/or Study*	*Notes and References*[12]
1889	*Albatross*	San Benedicto Socorro Clarión	Lt. Cdr. Z. L. Tanner, U.S.N., C. H. Gilbert, C. H. Townsend	Fish, plants, reptiles, dredgings, soundings	U.S. Commission of Fish and Fisheries cruise. Tanner (1892, pp. 432–436).
1897	*H. C. Wahlberg*	San Benedicto Socorro Clarión	A. W. Anthony (in charge)	Plants, fish, general collections	Expedition to the Islas Galápagos. Brandegee (1900, pp. 19, 26–28).
1897	*Lila* and *Mattie*	Clarión	Charles M. Harris	Birds, reptiles, insects	Expedition to Islas Galápagos sponsored by Walter Rothschild. See: F. Hamilton (1903. Hunting the giant tortoise. Wide World, XI: 4, 25–30). Additional information from Joseph R. Slevin (personal communication).
1897	U.S.S. *Boston*	Socorro	not known	——	Search for the lost brigantine *Tahiti*. Slevin (1931, p. 18).
1899	*Oaxaca*	San Benedicto Socorro Roca Partida Clarión	Cdr. E. Portes Ramírez, Sub-lieut. Arturo Puga, and Lieut. José Servín y L.	Geographical locations, maps, soundings	Sketch maps published by Muñoz Lumbier (1919, pp. 10–12, plates I–V). See also Mitchell (1933, pp. 124–125).
1903	*Mary Sachs*	Socorro Clarión	R. H. Beck (in charge)	Birds, shells, plants	California Academy of Sciences expedition. Except for a diary in the possession of E. W. Gifford all records and specimens were lost in the San Francisco fire of 1906 (Joseph R. Slevin, personal communication).

TABLE 4 *(Continued)*

Year	*Ship*	*Islands Visited*	*Investigator*[11]	*Chief Collections, and/or Study*	*Notes and References*[12]
1905	*Academy*	San Benedicto Socorro	R. H. Beck (in charge)	General zoological and botanical collecting, geology, photography	California Academy of Sciences expedition to the Islas Galápagos. Slevin (1931, pp. 16–18).
1923	*Velero II*	Socorro Clarión	Capt. Allan Hancock (in charge)	Exploration, photography	Discovered a large lava tunnel on the east side of Socorro. Narrative account by Banning (1925, pp. 28–38, 45–53).
1925	U.S.S. *Ortolan*	San Benedicto Socorro Roca Partida Clarión	G Dallas Hanna (in charge)	General zoological, botanical, and geological collecting, dredging, photography	California Academy of Sciences expedition to the Islas Revillagigedo and Islas Tres Marias. Hanna (1926, pp. 1–66).
1927 or 1928	not known	Socorro	not known	Sheep farming	For about one year a company operating out of Los Angeles (?) kept a sheep herder and his wife on Socorro. Guy Silva (personal communication).
1932	*Zaca*	Socorro Clarión	Harry S. Swarth (in charge)	General zoological and botanical collecting	Templeton Crocker–California Academy of Sciences expedition to the Islas Galápagos. Crocker (1933).
1933	*Progreso*	Socorro	Leon Furton (in charge)	Colonization study	Escuela Nacional de Agricultura expedition. Certain animals and plants were left on Socorro. Sánchez de la Peña (1948, p. 145).
1934	*Velero III*	Socorro Clarión	C. McLean Frazer (in charge)	Biology, photography	Two cruises. Allan Hancock expedition to the Islas Galápagos in the winter and spring and an early summer cruise to the Islas Revillagigedo. Frazer (1943, pp. 51–52).

Table 4 *(Continued)*

Year	*Ship*	*Islands Visited*	*Investigator*[11]	*Chief Collections, and/or Study*	*Notes and References*[12]
1936	*Zaca*	Clarión	William Beebe (in charge)	Dredging, trawling, fish	Templeton Crocker–Department of Tropical Research of the N.Y. Zoological Society expedition to the Gulf of California. Beebe (1937).
1938	U.S.S. *Houston*	Socorro	Waldo L. Schmitt	Fish	The presidential cruise of 1938. Schmitt (1939).
1939	*Velero III*	Socorro Clarión	C. McLean Frazer (in charge)	Biology, photography	Allan Hancock expedition to the Canal Zone. Frazer (1943, p. 53).
1946	*Zaca*	Socorro	Carl L. Hubbs	Fish	Errol Flynn expedition to Mexican islands and Acapulco. Carl L. Hubbs (personal communication).
1948	*Queretaro*	Socorro	Investigator in charge not known	General exploration, guano study, photography	Expedition sponsored by the Club Cinegético Coliman. Sánchez de la Peña (1948).
1948	*Tehuantepec* and *Papaloapan*	San Benedicto Socorro Roca Partida Clarión	Brig. Gen. de E. M. Rubén Calderón Aguilar (in charge)	General military and scientific observations, soils, photography, maps	Scientific and military expedition to the Mexican Pacific islands by the Escuela Superior de Guerra (1949, pp. 14–21, 159–163; Vivó Escoto, *Ibid.*, pp. 55–69). First soil analyses from Socorro and Clarión. Chemical analysis of water from the spring in Caleta Grayson.
1951	*Lang Syne*	Socorro	B. and P. Crowe	Exploration	Witnessed eruption of small cinder cone west of Lomas Colorados. Crowe (1955, p. 252).

TABLE 4 *(Continued)*

Year	*Ship*	*Islands Visited*	*Investigator*[11]	*Chief Collections, and/or Study*	*Notes and References*[12]
1952	*Marijean*	San Benedicto Socorro	D. H. Bates	Fish, photography	H. R. MacMillan fishing expedition to the Islas Galápagos. Photographs of San Benedicto were taken in February before the eruption in August. A privately printed booklet by Bates (1952) includes a translation of much of "Islas Revillagigedo" by Vivó Escoto (1949, pp. 55–69).
1952	*Observer*	San Benedicto	N. C. Bunker (in charge)	Geology, fish, photography, exploration of Volcán Bárcena	Woodrow Krieger–School of Tropical and Preventive Medicine of the College of Medical Evangelists expedition to the Islas Galápagos. A popular account of the exploration of Volcán Bárcena (Boquerón) was written by Richards and Walker (1954).
1953	*Paolina-T*	San Benedicto Socorro Roca Partida Clarión	B. H. Brattstrom, H. Dana, A. F. Richards	Biology, geology, soundings, submarine sampling, photography	University of California, Scripps Institution of Oceanography expedition. First rock samples from Roca Partida. Detailed soundings around islands.
1953	*Crest*	San Benedicto Socorro	A. F. Richards (in charge)	Underwater volcanic acoustics, botany, zoology, geochemistry, geology, soundings, photography	University of California, Scripps Institution of Oceanography expedition. An unpublished manuscript, "The Islas Revillagigedo Expedition of November, 1953," was prepared by members of the expedition. First known exploration by foot across the interior of Isla Socorro.

TABLE 4 *(Continued)*

Year	*Ship*	*Islands Visited*	*Investigator*[11]	*Chief Collections, and/or Study*	*Notes and References*[12]
1954	*Papaloapan*	Socorro	Pablo G. Franco (in charge)	Climatology, soil chemistry, botany, photography	Universidad de Guadalajara expedition. Medina G. (1957).
1955	*Crest*	San Benedicto Socorro Clarión	A. F. Richards (in charge)	Botany, zoology, geology, soil chemistry, soundings, photography	University of California, Scripps Institution of Oceanography expedition.
1957	*Papaloapan* (?)	Socorro	Capitán de Navío D. Hernandez Corvajal	—	Establishment of a Mexican naval garrison on Socorro, which is located on the lava flow comprising Cabo Rule.
1957	*Stranger*	San Benedicto Socorro Roca Partida Clarión	A. F. Richards (in charge)	Botany, geology, soils, tide gauge installation (Socorro), soundings, dredging, photography	University of California, Scripps Institution of Oceanography–Instituto de Geofísica, Universidad Nacional de México, expedition (SIGRE).

BIBLIOGRAPHY

The authors have tried to include all published references to the Islas Revillagigedo up to October, 1957, that could be personally checked, exclusive of maps, charts, and newspaper articles. In addition, early European historical and Mexican references have been included which the authors have not seen. All entries we have not examined are marked with an asterisk preceding the author's name. It is probable that a few isolated records have been overlooked; for example, a rare species of plant or animal from the islands may have been described in a monographic treatment of a specific group.

In some cases authors have mentioned general aspects of the biota of the islands in the introduction of a paper treating a particular phase or group of the biota. For example, many authors mention that there are birds on the islands. These comments, unless specific or pertinent, are not indexed separately in the subject index. Those publications discussing the general aspects of the biota of the islands will be found indexed under "General Description" or "General Natural History."

Some of the biological references cited have no specific Revillagigedo record (for example, Meek and Hildebrand, 1923–28), but they are a general review of a group in the region of the islands. Also, a few references either of general interest or applying to the zoogeography of the eastern Pacific are included even though they may not specifically mention the Islas Revillagigedo. Most of the biological references cited, however, do have Revillagigedo records.

We have not felt it necessary to cross-index junior or co-authors in the subject index.

AUTHORS

Adams, J. A. S.

1954. Uranium and thorium contents of volcanic rocks. *In* Nuclear geology. New York, John Wiley and Sons, Inc., pp. 89–98.

Allen, W. E.

1933. Surface phytoplankton obtained by the Templeton Crocker Expedition of the California Academy of Sciences of 1932. *Transactions of the American Microscopical Society*, 52:101–102.

Almada, Francisco R.

1939. Diccionario de historía, geografía y biografía del Estado de Colima. Colima, Tipográficos "Moderna," 190 pp.

Anonymous

*1621. Miroir, Oost et West-Indical, Auquel sont descriptes les deux dernieres Navigations, faictes, es Années 1614. 1615. 1617. & 1618. l'une par le

Anonymous—*Cont'd.*

renommé Guerrier de Mer, George de Spilbergen, par le Destroict de Magellan, & ainsi tout autor de toute la terre, avec toutes les Battailles données tant par terre que par eau. Icy sont aussi adioustées deux Histoires, l'une des Indes Orientales, l'autre des Indes Occidentales, avec le nombre des Navires, Forts, Soldats & Artillerie. L'autre faicte par Jacob le Maire, lequel au coste du Zud du Destroict de Magellan, a descouvert un nouveau Destroict. Avec la description de tuos Pays, Gens & Nations. Le tout embelli de belles Cartes & Figures a ce servantes. A Amsterdam, Chez Ian Iansz. sur l'Eau, a la Pas-carte: iv, 172 pp.

1901. Papers from the Hopkins Stanford Galápagos Expedition, 1898–1899. I. Introduction. *Proceedings of the Washington Academy of Science*, 3:363–364.

1952. Record volcano's sounds. *Science News Letter*, 62(22):351.

1953a. Volcano makes mud rain. *Ibid.*, 63(2):20.

1953b. San Benedicto wren joins extinct dodo bird. *Ibid.*, 63(20):308.

1957. Islas Revillagigedo. *Revista Técnica Obras Marítimas*, 10:49–53.

Anthony, A. W.

1896a. Land birds at sea. *Osprey*, 1:57–58.

1896b. Eggs of the black, Socorro, and least petrels. *Nidologist*, 4:16–17.

1898a. Petrels of southern California. *Auk*, 15:140–144.

1898b. Avifauna of the Revillagigedo Islands. *Ibid.*, 15:311–318.

1900. Nesting habits of the Pacific Coast species of the genus *Ruffinus* (sic). *Ibid.*, 17:247–252.

Arce, Manuel

1954. Misión en las Revillagigedo. *Revista de Revistas*, Agosto 22, 1954:18–25.

*Atlas Geográfico de la Estados Unidos Mexicanos

1946. Secretaría de Agricultura y Fomento, Direccion de Geografía, Meteorología y Hidrología, Tacumbaya, D. F.

Banda, Longinos

1862. Informe presentado al gobierno del Estado de Colima. *Boletín de la Sociedad Mexicana de Geografía y Estadística*, 9:183–186.

Banning, George Hugh

1925. In Mexican waters. Boston, Charles E. Lauriat Co., 196 pp.

Barnard, J. Laurens

1954. Amphipoda of the family ampiliscidae collected in the eastern Pacific by the *Velero III* and *Velero IV*. *University of Southern California Publications, Allan Hancock Expeditions*, 18(1):1–137.

Bates, D. H.

1952. Revilla Gigedo Islands Mexico. Portland, privately printed, 45 pp.

Beebe, William

1937. The Templeton Crocker Expedition. II. Introduction, itinerary, lists of stations, nets, and dredges. *Zoologica*, 22(2):33–46.

BEEBE, WILLIAM—*Cont'd.*

1938. Zaca venture. New York, Harcourt Brace and Co., 303 pp.

—— and JOCELYN CRANE

1947. Eastern Pacific expedition of the New York Zoological Society. XXXVII. Deep sea ceratioid fishes. *Zoologica*, 31(11):151–182.

—— and MARY V. PYL

1944. Eastern Pacific expeditions of the New York Zoological Society. XXXIII. Pacific Myctophidae (fishes). *Ibid.*, 29(9):59–95.

—— and J. TEE-VAN

1941a. Eastern Pacific expeditions of the New York Zoological Society. XXIV. Fishes from the tropical eastern Pacific (from Cedros Island, Lower California; south to the Galápagos Islands and northern Peru), Part 1. Lancelets and hag-fishes. *Ibid.*, 26(14):89–91.

1941b. Eastern Pacific expeditions of the New York Zoological Society. XXV. Fishes from the tropical eastern Pacific (from Cedros Island, Lower California; south to the Galápagos Islands and northern Peru), Part 2. Sharks. *Ibid.*, 26(15):93–122.

1941c. Eastern Pacific expeditions of the New York Zoological Society. XXVIII. Fishes from the tropical eastern Pacific (from Cedros Island, Lower California; south to the Galápagos Islands and northern Peru), Part 3. Rays, mantas, and chimaeras. *Ibid.*, 26(26):245–280.

BELCHER, EDWARD

1843. Narrative of a voyage round the world, performed in Her Majesty's Ship *Sulphur*, during the years 1836–1842, including details of the naval operations in China, from December 1840, to November 1841. 2 vols., London, Henry Colburn; 1:viii, 387 pp.; 2:vii, 474 pp.

BENT, A. C.

1948. Life histories of North American nuthatches, wrens, thrashers, and their allies. *Bulletin of the United States National Museum*, 195:1–475.

BLAKE, EMMET R.

1953. Birds of Mexico. University of Chicago Press, xxix, 644 pp.

BOGERT, CHARLES M., and JAMES A. OLIVER

1945. A preliminary analysis of the herpetofauna of Sonora. *Bulletin of the American Museum of Natural History*, 83(6):297–426.

BONAR, LEE

1939. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 38. Fungi from the Galápagos and other Pacific coastal islands. *Proceedings of the California Academy of Sciences*, 4th ser., 22(9): 195–206.

BOONE, LEE

1927. The littoral crustacea fauna of the Galápagos Islands. Part I. Brachyura. *Zoologica*, 8(4):127–288.

BOULENGER, GEORGE A.

1885. Catalogue of the lizards of the British Museum (Natural History). British Museum (Natural History), London, 2:xiii, 1–497.

(1052)

BRANDEGEE, T. S.

1898. New species of plants from Mexico. *Erythea*, 7:1–9.

1900. Voyage of the *Wahlberg*. *Zoe*, 5(2):19–28.

BRATTSTROM, BAYARD H.

1953. The Cactus of the Revillagigedo Islands, Mexico. *Cactus and Succulent Journal*, 25(6):181–182.

1955. Notes on the herpetology of the Revillagigedo Islands, Mexico. *American Midland Naturalist*, 54(1):219–229.

—— and THOMAS R. HOWELL

1956. The birds of the Revilla Gigedo Islands, Mexico. *Condor*, 58(2):107–120.

BREWSTER, W.

1903. Breeding grounds of the black and Socorro petrels—A correction. *Auk*, 20:63–64.

BROCK, VERNON E.

1943. Distributional notes on the fishes of Lower California and the west coast of Mexico. II. *Copeia*, 2:130–131.

BURKENROAD, MARTIN D.

1937. The Templeton Crocker Expedition. XII. Sergestidae (Crustacea, Decapoda) from the Lower California region, with descriptions of two new species and some remarks on the organs of Pesta in Sergestes. *Zoologica*, 22(25):315–329.

1938. The Templeton Crocker Expedition. XIII. Penaeidae from the region of Lower California and Clarión Island, with descriptions of four new species. *Ibid.*, 23(3):55–91.

BURNEY, JAMES

1803–1817. A chronological history of the discoveries in the South Sea or Pacific Ocean. 5 vols., London, n.p.

1803. 1. Commencing with an account of the earliest discovery of that sea by Europeans, and terminating with the voyage of Sir Francis Drake, in 1579, xx, 383 pp.

1806. 2. From the year 1579, to the year 1620, xiv, 482 pp.

1816. 4. To the year 1723, including a history of the buccaneers of America, xviii, 580 pp.

BURT, CHARLES E., and GEORGE S. MYERS

1942. Neotropical lizards in the collection of the Natural History Museum of Stanford University. *Stanford University Publications, University Series, Biological Sciences*, 8(2):1–52.

CHAPMAN, F. M., and L. GRISCOM

1924. The house wrens of the genus *Troglodytes*. *Bulletin of the American Museum of Natural History*, 50(4):279–304.

Clark, Hubert L.

1948. A report on the Echini of the warmer eastern Pacific, based on the collections of the *Velero III*. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 8(5):225–351.

Clark, Lois

1953. Some Hepaticae from the Galápagos, Cocos, and other Pacific coast islands. *Proceedings of the California Academy of Sciences*, 4th ser., 27(18):593–624.

Colnett, James

1798. A voyage to the south Atlantic and round Cape Horn into the Pacific Ocean, for the purpose of extending the spermaceti whale fisheries, and other objects of commerce, by ascertaining the ports, bays, harbours, and anchoring berths, in certain islands and coasts of those seas, at which the ships of the British merchants might be refitted. London, W. Bennett, 179 pp.

Contreras, Francisco

1926. Informe sobre la expedición del "*Ortolan*," rendido a la dirección de estudios biológicas. *Memorias (y Revista) de la Sociedad Científica "Antonio Alzate*," 45:13–35.

Cope, E. D.

1872. Description of the common lizard of Socorro. *Proceedings of the Boston Society of Natural History*, 14:303.

1900. The Crocodilians, lizards, and snakes of North America. *Report of the United States National Museum*, 1898:153–1270.

Crane, Jocelyn

1937. The Templeton Crocker Expedition. III. Brachygnathous crabs from the Gulf of California and the west coast of Lower California. *Zoologica*, 22(3):47–78.

1941. Eastern Pacific expeditions of the New York Zoological Society. XXVI. Crabs of the genus *Uca* from the west coast of Central America. *Ibid.*, 26(19):145–208.

1947. Eastern Pacific expeditions of the New York Zoological Society. XXXVIII. Intertidal brachygnathous crabs from the west coast of tropical America, with special reference to ecology. *Ibid.*, 32(9):69–95.

Crocker, Templeton

1933. The Templeton Crocker Expedition of the California Academy of Sciences. 1932. No. 2. Introductory Statement. *Proceedings of the California Academy of Sciences*, 4th ser., 21(2):3–12.

Crowe, Bill and Phyllis

1955. Heaven, hell and salt water. London, Adlard Coles Ltd., 264 pp.

Cushman, Joseph A.

1932– The foraminifera of the tropical Pacific collections of the *Albatross*, CUSHMAN, JOSEPH A.—*Cont'd.*

1942. 1899–1900. *Bulletin of the United States National Museum*, 161: Part 1. Astrorhizidae to Trochamminidae, 1932: iv, 83 pp.; Part 2. Lagenidae to Alveolinellidae, 1933: iv, 79 pp.; Part 3. Helerohelicidae and Buliminidae, 1942: v, 67 pp.

—— and IRENE MCCULLOCH

1939. A report on some arenaceous Foraminifera. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 6(1):1–113.

1940. Some Nonionidae in the collections of the Allan Hancock Foundation. *Ibid.*, 6(3):145–178.

1942. Some Virgulininae in the collections of the Allan Hancock Foundation. *Ibid.*, 6(4):179–230.

1948. The species of *Bulimina* and related genera in the collections of the Allan Hancock Foundation. *Ibid.*, 6(5):231–294.

1950. Some Lagenidae in the collections of the Allan Hancock Foundation. *Ibid.*, 6(6):295–364.

DALL, W. H.

1900. Additions to the insular land-shell faunas of the Pacific coast, especially of the Galápagos and Cocos Is. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 52:88–105.

1909. Report on a collection of shells from Peru, with a summary of the littoral marine Mollusca of the Peruvian Zoological Province. *Proceedings of the United States National Museum*, 37(1704):147–294.

1926. Expedition to the Revillagigedo Islands, Mexico, in 1925. Land shells of the Revillagigedo and Tres Marias Islands, Mexico. *Proceedings of the California Academy of Sciences*, 4th ser., 15(15):35–36.

—— and W. H. OCHSNER

1928. Landshells of the Galápagos Islands. *Ibid.*, 17(5):141–185.

DAWSON, E. YALE

1952. Resumen de las investigaciones recientes sobre algas marinas de la Costa Pacifica de México, con una sinopsis de la literatura, sinonima, y distribución de las especies descritas. *Revista de la Sociedad Mexicana de Historica Natural*, 13(1–4):97–197.

1954. The marine flora of Isla San Benedicto following the volcanic eruption of 1952–1953. *University of Southern California Publications, Allan Hancock Foundation, Occasional Paper* 16:1–25.

1957. Notes on eastern Pacific insular marine algae. *Los Angeles County Museum, Contributions in Science*, 8:1–8.

DEICHMANN, ELIZABETH

1937. The Templeton Crocker Expedition. IX. Holothurians from the Gulf of California, the west coast of Lower California, and Clarión Island. *Zoologica*, 22(10):161–176.

1938. Eastern Pacific expeditions of the New York Zoological Society. XVI. Holothurians from the western coasts of Lower California and Central America, and from the Galápagos Islands. *Ibid.*, 23(18):361–387.

DEICHMANN, ELIZABETH—*Cont'd.*

1941. The Holothurioidea collected by the *Velero III* during the years 1932–1938. Part I. Dendrochirota. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 8(3):61–195.

*DERROTERO DE LAS COSTAS DE LA REPUBLICA MEXICANA

1939. Secretaría de Comunicaciones y Obras Públicas, Dirección General de Marina, Puertos, y Faros, S.C.O.P. Narvarte, México, D. F.

DEWEY, GEORGE

1874. Remarks on the coast of Lower California and Mexico. *United States Hydrographic Office*, Publication no. 56, 60 pp.

DIETZ, ROBERT S. (edited by D. G. Kelley)

1953. Boquerón. *Pacific Discovery*, 6(1):24–27.

—— and ADRIAN F. RICHARDS

1953a. Volcanic eruption of San Benedicto Island, Mexico (Abstract). *Bulletin of the Geological Society of America*, 64(12):p. 5103.

1953b. Eruption on San Benedicto Island, Mexico, 1952 (Abstract). Eighth Pacific Science Congress, Abstracts of paper, supplement: 3–4.

DODGE, CARROL W.

1936. Lichens of the G. Allan Hancock Expedition of 1934, collected by Wm. R. Taylor. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 3(3):33–46.

DROUET, FRANCIS

1936. Myxophyceae of the G. Allan Hancock Expedition of 1934, collected by Wm. R. Taylor. *Ibid.*, 2(2):15–31.

DURHAM, J. WYATT

1947. Corals from the Gulf of California and the north Pacific coast of America. *Geological Society of America, Memoir*, 20:1–68.

1950. Cenozoic marine climates of the Pacific coast. *Bulletin of the Geological Society of America*, 61(11):1243–1264.

—— and J. LAURENS BARNARD

1952. Stony corals of the eastern Pacific collected by the *Velero III* and *Velero IV*. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 16(1):1–110.

EARDLEY, A. J.

1954. Tectonic relations of North and South America. *Bulletin of the American Association of Petroleum Geologists*, 38(5):707–773.

ESCUELA SUPERIOR DE GUERRA

1949. Mares e islas mexicanos del Pacífico, resultado de la expedición científico-militar de la Escuela Superior de Guerra, Mayo–Junio, 1948. Mexico, Published under the direction of General Brigadier de E. M. Rubén Calderón Aguilar, Director, 170 pp.

FISHER, WALTER K.

1952. Sipunculid worms of California and Baja California. *Proceedings of the United States National Museum*, 102(3306):371–450.

Fowler, Henry W.

1938. The fishes of the George Vanderbilt South Pacific Expedition, 1937. *Academy of Natural Sciences of Philadelphia, Monograph*, 2:1–349.

1944. Results of the fifth George Vanderbilt Expedition (1941). Bahamas, Caribbean Sea, Panama, Galapagos Archipelago, and Mexican Pacific Islands. The fishes. *Ibid.*, 6:57–530.

Fraser, C. McLean

1938. Hydroids of the 1934 Allan Hancock Pacific Expedition. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 4(1):1–105.

1939. Distribution of the hydroids in the collections of the Allan Hancock Expeditions. *Ibid.*, 4(4):155–170.

1940. Hydroid distribution in the Pacific. *Proceedings of the Sixth Pacific Science Congress*, 3:495–500.

1943. General account of the scientific work of the *Velero III* in the eastern Pacific, 1931–41. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 1(1–3):1–445.

1948. Hydroids of the Allan Hancock Pacific Expedition since March, 1938. *Ibid.*, 4(5):179–335.

Friedmann, H., L. Griscom, and R. T. Moore

1950. Distributional check-list of the birds of Mexico. *Pacific Coast Avifauna*, 29:1–202.

*Galvaom

1731. Tratado dos descobrimentos, Gomara, Congreso de México, fol. 116.

García Cubas, Antonio

1888–1891. Diccionario geográfico, histórico y biográfico de los Estados Unidos Mexicanos. 5 vols., México, Oficina Tipográfica de la Secretaría de Fomento.

1888. 2. 1–502.

1890. 4. 1–480.

1891. 5. 1–567.

Garman, Samuel

1899. Concerning a species of lizard from Clipperton Island. *Proceedings of the New England Zoological Club*, 1:59–62.

Garth, John S.

1940. Some new species of Brachyuran crabs from Mexico and the Central and South American mainland. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 5(3):51–128.

1946a. Littoral Brachyuran fauna of the Galápagos Archipelago. *Ibid.*, 5(10):341–602.

1946b. Distribution studies of Galápagos Brachyura. *Ibid.*, 5(11):603–638.

Gentry, Howard S.

1949. Land plants collected by the *Velero III*, Allan Hancock Pacific Expeditions, 1937–1941. *Ibid.*, 13(2):7–245.

GIESBRECHT, W.

1895. Reports on the dredging operations off the west coast of Central America to the Galápagos, to the west coast of Mexico, and in the Gulf of California, in charge of Alexander Agassiz, carried on by the U. S. Fish Commission steamer *Albatross* during 1891, Lieut. Commander Z. L. Tanner, U.S.N., commanding. XVI. Die Pelogischen Copepoden. *Bulletin of the Museum of Comparative Zoology, Harvard University*, 25(12):243–263.

GIFFORD, E. W.

1913. The birds of the Galápagos Islands, with observations on the birds of Cocos and Clipperton Islands (Columbiformes to Pelecaniformes). *Proceedings of the California Academy of Sciences*, 4th ser., 2:1–132.

GILBERT, CHARLES H.

1891a. Scientific results of explorations by the U. S. Fish Commission steamer *Albatross*. XII. A preliminary report on the fish collected by the steamer *Albatross* on the Pacific coast of North America during the year 1889, with descriptions of twelve new genera and ninety-two new species. *Proceedings of the United States National Museum*, 13(797):49–126.

1891b. Scientific results of explorations by the U. S. Fish Commission steamer *Albatross*. XXII. Descriptions of thirty-four new species of fish collected in 1888 and 1889, principally among the Santa Barbara Islands and in the Gulf of California. *Ibid.*, 14(880):539–566.

1897. Descriptions of twenty-two new species of fishes collected by the steamer *Albatross* of the United States Fish Commission. *Ibid.*, 19(1115):437–457.

GODMAN, FREDERICK DU CRANE

1907–1910. A monograph of the petrels (order *Tubinares*). London, Witherby and Co., lv, 381 pp.

GÓMEZ MONCADA, MANUEL

1958. Isla Socorro, Revista Técnica obras Marítimas, 21:22–25.

GRAYSON, ANDREW J. (edited by Geo. N. Lawrence)

1872. Exploring expedition to the Island of Socorro, from Mazatlan, Mexico. *In* The physical geography and natural history of the islands of the Tres Marias and of Socorro, off the western coast of Mexico. *Proceedings of the Boston Society of Natural History*, 14:287–297.

*GRIJALVA

Hist. de la Orden de S. Aug. en la N. Espan. Edad. 1, cap. 34 and seg.

GRINNELL, JOSEPH

1928. A distributional summation of the ornithology of Lower California. *University of California Publications in Zoology*, 32(1):1–300.

HANNA, G DALLAS

1925. Was there a Pacific continent? *Science*, 62(1613):491–492.

HANNA, G DALLAS—*Cont'd.*

1926. Expedition to the Revillagigedo Islands, Mexico, in 1925. *Proceedings of the California Academy of Sciences*, 4th ser., 15(1):113 pp.

1927. Geology of west Mexican Islands. *Pan-American Geologist*, 48(1):1–24.

1932. The Templeton Crocker Expedition of the California Academy of Sciences. *Science*, 76 (1974):375–377.

—— and A. M. STRONG

1949. West American mollusks of the genus *Conus*. *Proceedings of the California Academy of Sciences*, 4th ser., 26(9): 247–322.

HARTMAN, OLGA

1939. Polychaetous annelids. Part I. Aphroditidae to Pisionidae. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 7(1):1–156.

1940. Polychaetous annelids. Part II. Chrysopetalidae to Goniadidae. *Ibid.*, 7(3):173–288.

1941. Polychaetous annelids. Part IV. Pectinariidae, with a review of all species from the Western Hemisphere. *Ibid.*, 7(5):325–346.

1944. Polychaetous annelids. Part V. *Eunicea*. *Ibid.*, 10(1):1–237.

1946. Polychaetous annelids. Part VI. Paraonidae, Magelonidae, Longosomidae, Ctenodrilidae, and Sabellariidae. *Ibid.*, 10(3):311–389.

1947a. Polychaetous annelids. Part VII. Capitellidae. *Ibid.*, 10(4):391–481.

1947b. Polychaetous annelids. Part VIII. Pilargiidae. *Ibid.*, 10(5):483–523.

1950. Goniadidae, Glyceridae, and Nephtyidae. *Ibid.*, 15(1):1–181.

HEIDEMANN, OTTO

1901. Papers from the Hopkins Stanford Galápagos Expedition, 1898–1899. I. Entomological results (1). Hemiptera. *Proceedings of the Washington Academy of Sciences*, 3:336–370.

HELLER, EDMUND, and ROBERT E. SNODGRASS

1903. Papers from the Hopkins Stanford Galápagos Expedition, 1898–1899, XV. New fishes. *Proceedings of the Washington Academy of Sciences*, 5: 189–229.

HENDRICK, JOYCE

1942. Some lichens from the American tropics collected by Wm. R. Taylor. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 3(9): 51–64.

HERRE, ALBERT W.

1940. Distribution of fish in the tropical Pacific. *Proceedings of the Sixth Pacific Science Congress*, 3:587–592.

*HERRERA

Hist. de las Ind. Occid., Dec. 7. lib. 5.

HERTLEIN, LEO G.

1938. A note on some species of marine mollusks occurring in both Polynesia

(1059)

HERTLEIN, LEO G.—*Cont'd.*

and the western Americas. *Proceedings of the American Philosophical Society*, 78(2):303–312.

—— and A. M. STRONG

1940. Eastern Pacific expeditions of the New York Zoological Society. XXII. Mollusks from the west coast of Mexico and Central America. Part 1. *Zoologica*, 25(25):369–430.

1943. *Ibid.* XXXII. Part 2. *Ibid.*, 28(19):149–168.

1946a. *Ibid.* XXXIV. Part 3. *Ibid.*, 31(5):53–76.

1946b. *Ibid.* XXXV. Part 4. *Ibid.*, 31(8):93–120.

1947. *Ibid.* XXXVI. Part 5. *Ibid.*, 31(10):129–150.

1948. *Ibid.* XXXIX. Part 6. *Ibid.*, 33(13):163–198.

1949a. *Ibid.* XL. Part 7. *Ibid.*, 34(9):63–97.

1949b. *Ibid.* XLI. Part 8. *Ibid.*, 34(19):239–258.

1950. *Ibid.* XLII. Part 9. *Ibid.*, 35(19):217–252.

1951. *Ibid.* XLIII. Part 10. *Ibid.*, 36(5):67–120.

HITCHCOCK, A. S.

1935. The Templeton Crocker Expedition of the California Academy of Sciences, 1932, No. 24. New species of grasses from the Galápagos and Revillagigedo Islands. *Proceedings of the California Academy of Sciences*, 4th ser., 21(24):295–300.

HOLTHUIS, LIPKE B.

1951. A general revision of the Palamonidae (Crustacea, Decapoda, Natantia) of the Americas. I. The subfamilies Euryrhynchinae and Pontoniinae. *University of Southern California Publications, Allan Hancock Foundation, Occasional Paper* 11:1–332.

1952. A general revision of the Palamonidae (Crustacea, Decapoda, Natantia) of the Americas. II. The subfamily Paleamoninae. *Ibid.*, 12:1–396.

HOWE, MARSHALL A.

1934. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 17. The Hepaticae (chiefly Riccia and Anthocerotocea) of the Galápagos Islands and the coast and islands of Central America and Mexico. *Proceedings of the California Academy of Sciences*, 4th ser., 21(17):199–210.

HUBBS, CLARK

1953. Revision of the Eastern Pacific fishes of the clinid genus *Labrisomus*. *Zoologica*, 38(9):113–136.

HUMBOLDT, ALEXANDER

1811. Political essay on the kingdom of New Spain. Translated from the original French by John Black. 2 vols., London, Longman, Hurst, Rees, Orne and Brown, and H. Colburn. 1:i–xii, i–cxv, 1–221; 2:1–377.

(IMRAY, JAMES)

1853. Sailing directions for the west coast of North America. London, James Imray, 232 pp.

IMRAY, JAMES

1868. Sailing directions for the west coast of North America between Panama and Queen Charlotte Islands. 2nd Ed., London, James Imray and Sons, 380 pp.

INGRAM, WILLIAM MARCUS

1948. The Cypraeid fauna of the Galápagos Islands. *Proceedings of the California Academy of Sciences*, 4th ser., 26(7):135–145.

JOHNSTON, IVAN M.

1931. The flora of the Revillagigedo Islands. *Ibid.*, 20(2):9–104.

JORDAN, D. S., and B. W. EVERMANN

1896– The fishes of North and Middle America. *Bulletin of the United States*
1900. *National Museum*, 47:1–3313.

—— and C. H. GILBERT

1881. Notes on a collection of fishes, made by Lieut. Henry E. Nichols, U.S.N. on the west coast of Mexico, with descriptions of new species. *Proceedings of the United States National Museum*, 4:225–233.

—— and R. C. MCGREGOR

1898. List of fishes collected at the Revillagigedo Archipelago and neighboring islands. *Report of the Commissioner, U.S. Commission of Fish and Fisheries*, 24:271–284.

KAEDING, H. B.

1905. Birds from the west coast of Lower California and adjacent islands. *Condor*, 7:105–111, 134–138.

LALICKER, C. G., and IRENE MCCULLOCH

1940. Some Textulariidae of the Pacific Ocean. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 6(2):115–143.

LAMB, C. C.

1925. The Socorro Warbler added to the A. O. U. checklist. *Condor*, 27:36–37.

LAWRENCE, GEORGE W.

1871. Descriptions of new species of birds from Mexico, Central America, with a note on *Rallus longirostris*. *Annals of the Lyceum of Natural History of New York*, 10:1–21.

1872. On the physical geography and natural history of the islands of Tres Marias and of Socorro, off the western coast of Mexico. *Proceedings of the Boston Society of Natural History*, 14:261–302.

LIGHT, S. F.

1930. Termites collected by T. T. Craig on Socorro Island. *Pan-Pacific Entomologist*, 6:178–180.

1935. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 20. The Termites. *Proceedings of the California Academy of Sciences*, 4th ser., 21(20):233–258.

Linder, D. H.

1934. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 18. Lichens. *Ibid.*, 21(18):211–222.

Loomis, L. M.

1918. Expedition of the California Academy of Sciences to the Galápagos Islands, 1905–1906. XII. A review of the albatrosses, petrels, and diving petrels. *Ibid.*, 2(2):1–187.

McLellan, Mary E.

1925. Expedition of the California Academy of Sciences to the Revillagigedo Islands. *Science*, 62(1599):171–173.

1926. Expedition to the Revillagigedo Islands, Mexico, in 1925. VI. The birds and mammals. *Proceedings of the California Academy of Sciences*, 4th ser., 15:279–322.

Mann, Albert

1907. Report on the diatoms of the *Albatross* voyages in the Pacific Ocean. 1880–1904. *Contributions of the United States National Herbarium*, 10(5):221–242.

Manter, Harold W.

1940a. Digenetic trematodes of fishes from the Galápagos Islands and the neighboring Pacific. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 2(14):329–497.

1940b. The geographical distribution of Digenetic trematodes of marine fishes of the tropical American Pacific. *Ibid.*, 2(16):531–547.

*May, Jan Cornelisz

See Anonymous, 1621.

Medina G., Manuel

1957. Memoria de la expedición científica a las Islas Revillagigedo. Guadalajara Imprenta Universitaria, 244 pp.

Meek, S. E. and S. F. Hildebrand

1923–1928. The marine fishes of Panama. *Field Museum of Natural History, Zoological Series*, 15:1–1045.

Meinertzhagen, R.

1926. Introduction to a review of the genus *Corvus*. *Novitates Zoological*, 33: 57–121.

Menard, Henry W.

1955a. Fractures in the Pacific floor. *Scientific American*, 193(1):36–41.

1955b. Deformation of the northeastern Pacific basin and the west coast of North America. *Bulletin of the Geological Society of America*, 66(9):1149–1198.

(1062)

MESERVE, FRANK C.

1938. Some monogenetic trematodes from the Galápagos Islands and the neighboring Pacific. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 2(5):31–89.

MEXICO

1955. Constitución política de los Estados Unidos Mexicanos. Art. 42 (p. 37), Mexico, Editorial Porrua, S. A., 4th ed., 100 pp.

MITCHELL, JULIO

1933. Principales islas del Golfo de California y el Archipiélago de las Revillagigedo. *Primer Centenario de la Sociedad Mexicana de Geografía Estadística*, 1833–1933, 1:103–126.

MITTLEMAN, M. B.

1942. A summary of the iguanid genus *Urosaurus*. *Bulletin of the Museum of Comparative Zoology, Harvard University*, 91(2):103–181.

MORENO RESÉNDIZ, SAÚL

1948. Observaciones acerca de la Isla del Socorro del Archipiélago de Revillagigedo. *Revista de Economía*, 11(4):25–28.

MORRELL, BENJAMIN, JR.

1832. A narrative of four voyages to the South Sea, north and south Pacific Ocean, Chinese Sea, Ethiopic and southern Atlantic Ocean, Indian and Antarctic Ocean, from the year 1822 to 1831. New York, J and J Harper, 492 pp.

MUÑOZ LUMBIER, MANUEL

1919. Algunos datos sobre las islas Mexicanas. *Anales del Instituto Geológico de México*, 7:1–56.

1946. Las Islas Mexicanas. Biblioteca Enciclopédica Popular. Tomo 117, Mexico, Secretaría de Educacion Pública, viii, 126 pp.

MYERS, GEORGE S.

1940. The fish fauna of the Pacific Ocean, with especial references to zoogeographical regions and distribution as they affect the international aspects of the fisheries. *Proceedings of the Sixth Pacific Science Congress*, 3:201–210.

OBERHOLSER, HARRY C.

1898. A revision of the wrens of the genus *Thryomanes* Sclater. *Proceedings of the United States National Museum*, 21(1153):421–450.

1904. A review of the wrens of the genus *Troglodytes*. *Ibid.*, 27(1354):197–210.

1917a. Notes on North American birds, III. *Auk*, 34:465–470.

1917b. Notes on the genus *Puffinus* Brisson. *Ibid.*, 34:471–475.

1917c. A review of the subspecies of the leach petrel, *Oceanodroma leucorhoa* (Vieillot). *Proceedings of the United States National Museum*, 54 (2230):165–171.

1918. The common ravens of North America. *Ohio Journal of Science*, 18:213–225.

Orr, Robert T.

1940. The distribution of the more important marine mammals of the Pacific Ocean, as it affects their conservation. *Proceedings of the Sixth Pacific Science Congress*, 3:217–222.

Ortenburger, A. I.

1923. A note on the genera *Coluber* and *Masticophis*, and a description of a new species of *Masticophis*. *Museum of Zoology, University of Michigan, Occasional Paper*, 139:1–7.

1928. The whip snakes and racers, genera *Masticophis* and *Coluber*. *Memoirs of the University of Michigan*, 1:1–247.

Orton, Grace L.

1955. Separation of eggs of synentognath and allotriognath fishes in early embryonic stages. *California Fish and Game*, 41(1):105–106.

Osburn, Raymond C.

1950. Bryozoa of the Pacific coast of America. Part I. Cheilostomata Anasca. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 14(1):1–269.

1952. Bryozoa of the Pacific coast of America. Part II. Cheilostomata Ascophora. *Ibid.*, 14(2):270–611.

1953. Bryozoa of the Pacific coast of America. Part III. Cyclostomata, Ctenostomata, Entoprocta, and addenda. *Ibid.*, 14(3):612–841.

Pilsbry, Henry A.

1898. A new land shell from Clarión Island. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 50: p. 354.

*Ramusio's Collection

1613. Edition of Venice, 1:370–375.

Rathbun, Mary J.

1924. Brachyuran crabs collected by the Williams Galápagos Expedition, 1923. *Zoologica*, 5(14):153–159.

1937. The Oxystomatous and allied crabs of America. *Bulletin of the United States National Museum*, 166:vi, 278 pp.

Rehn, James A. G.

1913. Descriptions and records of South American Orthoptera, with the description of a new subspecies from Clarión Island. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 65:82–113.

Revere, Joseph Warren

1947. Naval duty in California (reprint of: A tour of duty in California. New York, C. S. Francis Co., 1849). Oakland, Biobooks, 245 pp.

Richards, Adrian F.

1953. Continued volcanic activity at San Benedicto Island, Mexico. *Volcano Letter* (Hawaii), 519: p. 7.

Richards, Adrian F.—*Cont'd.*

1956. Volcanism in eastern Pacific basin: 1945–1955 (Abstract). Resumenes de los trabajos presentados, 20th International Geological Congress: p. 18.

1957a. Geology, volcanology, and bathymetry of Isla San Benedicto, Mexico. Unpublished Ph.D. Dissertation, University of California, Los Angeles, 225 pp.

1957b. Geology of the Islas Revillagigedo, Mexico (Abstract). *Bulletin of the Geological Society of America*, 68(12):p. 1843.

1957c. Identification of Isla San Benedicto, Mexico, pumice on islands in the central Pacific Ocean (Abstract). *Bulletin of the Geological Society of America*, 68(12):p. 1785.

1958a. Volcanism in eastern Pacific Ocean basin: 1945–1955. *Proceedings of the 20th International Geological Congress*, in press.

1958b. Transpacific distribution of floating pumice from Isla San Benedicto, Mexico. *Deep-sea Research*, 5:29–35.

—— and Robert S. Dietz

1956. Eruption of Bárcena Volcano, San Benedicto Island, Mexico. *Proceedings of the Eighth Pacific Science Congress*, 2:157–176.

—— and Lewis Wayne Walker

1954. Operation cremation. *Natural History*, 63(2):56–64.

Ridgeway, Robert

1883. Catalogue of the aquatic and fish-eating birds exhibited by the United States National Museum at the International Fisheries Exhibition, London, 1883. *Bulletin of the United States National Museum*, 27:139–184.

1884. Descriptions of some new North American birds. *Proceedings of the Biological Society of Washington*, 2:89–95.

1887. A manual of North American birds. Philadelphia, J. B. Lippincott Co., 631 pp.

Rust, Helen

1955. A report on the family Archidae (Pelecypoda). *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 20(2): 177–248.

Sánchez de la Peña, Mariano

1948. Datos sobre la reciente expedición al archipiélago de "Revillagigedo." *Boletín de la Sociedad Mexicana de Geografía y Estadística*, 65(1):141–167.

Scammon, Charles M.

1874. The marine mammals of the north-western coast of North America described and illustrated: together with an account of the American whale-fishery. San Francisco, John H. Carmany and Co., New York, G. P. Putnam's Sons, 1–319, v pp.

—— and Edward Drinker Cope

1869. On the Cetaceans of the west coast of North America. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 21:13–63.

SCHMIDT, KARL P.

1922. The amphibians and reptiles of Lower California and neighboring islands. *Bulletin of the American Museum of Natural History*, 46(11): 607–707.

SCHMITT, WALDO L.

1939. The presidential cruise of 1938. *In* Exploration and fieldwork of the Smithsonian Institution in 1938. Smithsonian Publication 3525:3–14.

1940. The Stomatopods of the west coast of America based on collections made by the Allan Hancock Expeditions, 1933–38. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 5(4):129–226.

SCHOTT, CHARLES A.

1883. Terrestrial magnetism-Collection of results for declination, dip and intensity, from observations made by the United States Coast and Geodetic Survey between 1833 and 1882, July. *In* Report of the United States Coast and Geodetic Survey showing the progress of the work during the fiscal year ending with June, 1881. Appendix 9, United States Coast and Geodetic Survey: 159–224.

SCHULTZ, LEONARD P., EARL S. HERALD, ERNEST A. LACHNER, ARTHUR D. WELANDER, and LOREN P. WOODS

1953. Fishes of the Marshall and Marianas Islands. *Bulletin of the United States National Museum*, 202:xxxii, 1–685 pp.

SECRETARÍA DE AGRICULTURA Y FOMENTO

1934. Acuerdo que declara no colonizables los terrenos de la isla Socorro del archipiélago de Revillagigedo. *In* Diario Oficial, México, Seccion 2, 86 (37), 24 Octubre de 1934: 1089–1090.

SETCHELL, W. A.

1937. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 34. Report on the Sargassums. *Proceedings of the California Academy of Sciences*, 4th ser., 22(5):127–158.

—— and N. L. GARDNER

1930. Marine algae of the Revillagigedo Islands expedition in 1925. *Ibid.*, 19(11): 109–215.

1937. A preliminary report on the algae. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 31. *Ibid.*, 22(2):65–98.

SLEVIN, JOSEPH R.

1926. Notes on a collection of reptiles and amphibians from the Tres Marias and Revillagigedo Islands, and west coast of Mexico, with description of a new species of Tantilla. *Ibid.*, 15(3):195–207.

1931. Log of the schooner "*Academy*." *Occasional Papers of the California Academy of Sciences*, 17:1–162.

SMITH, HOBART M., and E. H. TAYLOR

1945. An annotated checklist and key to the snakes of Mexico. *Bulletin of the United States National Museum*, 187:1–239.

SMITH, HOBART M., and E. H. TAYLOR—*Cont'd.*

1951. An annotated checklist and key to the reptiles of Mexico, exclusive of the snakes. *Ibid.*, 199:1–253.

SNODGRASS, JAMES M., and ADRIAN F. RICHARDS

1956. Observations of underwater volcanic acoustics at Bárcena Volcano, San Benedicto Island, Mexico, and in Shelikof Strait, Alaska. *Transactions of the American Geophysical Union*, 37(1):97–104.

SNODGRASS, ROBERT E., and E. HELLER

1902. Papers from the Hopkins Stanford Galápagos Expedition, 1898–1899. XI. The birds of Clipperton and Cocos Islands. *Proceedings of the Washington Academy of Science*, 4:501–520.

1904. Papers from the Hopkins Stanford Galápagos Expedition, 1898–1899. XVI. Birds. *Ibid.*, 5:231–372.

1905. Papers from the Hopkins Stanford Galápagos Expedition, 1898–1899. XVII. Shore fishes of the Revillagigedo, Clipperton, Cocos, and Galápagos Islands. *Ibid.*, 6:333–427.

SOOT-RYEN, TRON

1955. A report on the family Mytilidae (Pelecypoda). *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 20(1):1–174.

STEERE, WILLIAM C.

1946. The Bryophyta of the Allan Hancock Expedition of 1939. *Ibid.*, 13(1):1–4.

STEJNEGER, L.

1901. Description of a new species of snake from Clarión Island, west coast of Mexico. *Proceedings of the United States National Museum*, 23:715–717.

STEARNS, ROBERT E. C.

1894. The shells of the Tres Marias and other localities along the shores of Lower California and the Gulf of California. *Ibid.*, 17:139–204.

STRONG, A. M., and G D. HANNA

1930. Marine Mollusca of the Revillagigedo Islands, Mexico. *Proceedings of the California Academy of Sciences*, 4th ser., 19(2):7–12.

SVENSON, H. K.

1939. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 37. The Cyperaceae. *Ibid.*, 22(8):187–193.

TAKI, ISAO

1940. Chitons in the Pacific Ocean. *Proceedings of the Sixth Pacific Science Congress*, 3:487–491.

TAMAYO, JORGE L.

1949. Geografía general de México. Geografía física, 2 vols., Mexico, n.p., 1: i–viii, 1–628; 2:1–583.

TANNER, WILMER W.

1944. A taxonomic study of the genus *Hypsiglena*. *Great Basin Naturalist*, 5(3–4):25–92.

TANNER, Z. L.

1892. Report upon the investigations of the United States Fish Commission steamer *Albatross* for the year ending June 30, 1889. *In Report of the Commissioner for 1888*, Part 16, United States Commission of Fish and Fisheries: 395–512.

TATTERSALL, WALTER M.

1951. A review of the Mysidacea of the U. S. National Museum. *Bulletin of the United States National Museum*, 201:x, 1–292.

TAYLOR, WILLIAM R.

1945. Pacific marine algae of the Allan Hancock Expeditions to the Galápagos Islands. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 12:1–518.

TEE-VAN, JOHN

1940. Eastern Pacific expeditions of the New York Zoological Society. XVII. A review of the American fishes of the family Cerrhitidae. *Zoologica*, 25(5):53–64.

TOSCANO, RICARDO

1940. Islas de la República Mexicana. *Boletín de la Sociedad Mexicana de Geografíca y Estadística*, 54(5–6):245–385.

TOWNSEND, CHARLES H.

1891a. Scientific results of exploration by the U. S. Fish Commission steamer *Albatross*. No. XIV. Birds from the coasts of western North America and adjacent islands, collected in 1888–89, with descriptions of new species. *Proceedings of the United States National Museum*, 13(799): 131–142.

1891b. Scientific results of exploration by the U. S. Fish Commission steamer *Albatross*. No. XV. Reptiles from Clarión and Socorro Islands and the Gulf of California, with description of a new species. *Ibid.*, 13(800): 143–144.

1901. Dredging and other records of the steamer *Albatross*, with bibliography relative to the work of the vessel. *Report of the Commissioner*, Part 26, United States Commission of Fish and Fisheries: 387–562.

TREADWELL, AARON L.

1937. The Templeton Crocker Expedition. VIII. Polychaetous annelids from the west coast of Lower California, the Gulf of California, and Clarión Island. *Zoologica*, 22(9):139–160.

UNITED STATES BOARD ON GEOGRAPHIC NAMES

1952. Decisions on names in Mexico. Cumulative decision list 5209, United States Department of the Interior, 11 pp.

UNITED STATES COAST AND GEODETIC SURVEY

1883. Report of the U. S. Coast and Geodetic Survey showing the progress of the work during the fiscal year ending with June, 1881. Part 2, Brief abstracts of work accomplished, United States Coast and Geodetic Survey: 10–51.

(1068)

UNITED STATES NAVY HYDROGRAPHIC OFFICE

1880. Revilla Gigedo Islands. *In* The west coast of Mexico from the boundary line between the United States and Mexico to Cape Corrientes, including the Gulf of California. Publication no. 56 revised: 195–198.

1949. Weather summary, Mexico, Publication no. 532, 220 pp.

1951. Revilla Gigedo Islands. *In* Sailing directions for the west coasts of Mexico and Central America. Publication no. 84, 9th ed.: 21–25.

1952. Volcanic activity North Pacific. *Hydrographic Bulletin*, no. 32, August 9.

VAN CLEAVE, HARLEY J.

1940. The Acanthocephala collected by the Allan Hancock Pacific Expedition, 1934. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 2(15):501–527.

VAN DENBURGH, JOHN

1895. A review of the herpetology of Lower California, Part I. Reptiles. *Proceedings of the California Academy of Sciences*, 2nd ser., 5:77–162.

1905. The reptiles and amphibians of the Islands of the Pacific coast of North America from the Farallons to Cape San Lucas and the Revilla Gigedos. *Ibid.*, 3rd ser., 4(1):1–28.

1922. The reptiles of western North America. *Occasional Papers of the California Academy of Sciences*, 10:1–1028.

—— and J. R. SLEVIN

1914. Reptiles and amphibians of the islands of the west coast of North America. *Proceedings of the California Academy of Sciences*, 4th ser., 4:129–152.

VAN DUZEE, E. P.

1933. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 4. Characters of twenty-four new species of Hemiptera from the Galápagos Islands and the coast islands of Central America. *Proceedings of the California Academy of Sciences*, 4th ser., 21(4):25–40.

1934. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 12. The Diurnal Lepidoptera of the expedition. *Ibid.*, 12(12): 139–146.

VASEY, G., and J. N. ROSE

1891. Plants collected in 1889 at Socorro and Clarión Islands, Pacific Ocean. *Proceedings of the United States National Museum*, 13(801):145–149.

VIVÓ ESCOTO, JORGE A.

1949. Islas Revillagigedo. *In* Mares e islas Mexicanos del Pacífico, resultado de la expedición científico-militar de la Escuela Superior de Guerra, Mayo-Junio, 1948. Mexico, Published under the direction of General Brigadier de E. M. Rubén Calderón Aguilar, Director: 55–69.

WAGNER, HENRY R.

1937. The cartography of the northwest coast of America to the year 1800. 2 vols., Berkeley, University of California Press, 1:xiv, 270 pp.; 2:271–543.

WALLACE, A. R.

1876. The geographic distribution of animals. Vol. 2, New York, Harper and Bros., 553 pp.

WEBSTER, J. D., and R. T. ORR

1954. Miscellaneous notes on Mexican birds. *Wilson Bulletin*, 66:267–269.

WHEELER, WILLIAM M.

1933. The Templeton Crocker Expedition of the California Academy of Sciences, 1932. No. 6. Formicidae of the Templeton Crocker Expedition. *Proceedings of the California Academy of Sciences*, 4th ser., 21(6):57–64.

WILLIAMS, HOWEL

1952. Recent eruption on San Benedicto Island, Mexico. *Volcano Letter*. (Hawaii), 517: p. 7.

WILSON, CHARLES B.

1937. Parasitic copepods taken during the third Hancock Expedition to the Galápagos Islands. *University of Southern California Publications, Allan Hancock Pacific Expeditions*, 2(4):23–31.

1950. Copepods gathered by the U. S. Fisheries steamer *Albatross* from 1887 to 1909, chiefly in the Pacific Ocean. *Bulletin of the United States National Museum*, 100(14, part 4):141–441.

YARZA, LUZ ESPERANZA

1948. Los volcanes de México. Mexico, Sociedad Mexicana de Geografía y Estadística, xvi, 187 pp.

ZIESENHENNE, FRED C.

1937. The Templeton Crocker Expedition. X. Echinoderms from the west coast of Lower California, the Gulf of California, and Clarión Island. *Zoologica*, 22(15):209–239.

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U. S. Coast and Geodetic Survey, 1883
U. S. Navy Hydrographic Office, 1880, 1951
Vivó Escoto, 1949
Wallace, 1876

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Almada, 1939
*Anonymous, 1621
Banda, 1862
Belcher, 1843
Brandegee, 1900
Burney, 1803, 1806, 1816
Colnett, 1798
Escuela Superior de Guerra, 1949
*Galvaom, 1731
García Cubas, 1888, 1890, 1891
*Grijalva
Hanna, 1926
*Herrera
Humboldt, 1811
Medina G., 1957
Mexico, 1955
Mitchell, 1933
Muñoz Lumbier, 1919, 1946
*Ramusio's Collection, 1613
Secretaría de Agricultura y Fomento, 1934
Tamayo, 1949
U. S. Board on Geographic Names, 1952
U. S. Coast and Geodetic Survey, 1883
U. S. Navy Hydrographic Office, 1880
Vivó Escoto, 1949
Wagner, 1937

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Adams, 1954
Anonymous, 1952, 1953a
Crowe, 1955
Dietz, 1953
Dietz and Richards, 1953a, 1953b
Eardley, 1954
Hanna, 1925, 1926, 1927
Medina G., 1957
Menard, 1955a, 1955b
Revere, 1947
Richards, 1953, 1956, 1957a, 1957b, 1958a, 1958b
Richards and Dietz, 1956
Richards and Walker, 1954
Snodgrass and Richards, 1956
U. S. Navy Hydrographic Office, 1952
Wallace, 1876
Williams, 1952
Yarza, 1948

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Beebe, 1937, 1938
Brandegee, 1900
Brattstrom, 1955
Brattstrom and Howell, 1956
Contreas, 1926
Crocker, 1933
Escuela Superior de Guerra, 1949
Fraser, 1943
Grayson, 1872
Hanna, 1926
Lawrence, 1872
Medina G., 1957
Slevin, 1931
Wallace, 1876

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Brattstrom, 1955 (Reptiles)
Brattstrom and Howell, 1956 (Birds)
Durham, 1947, 1950 (Corals)
Moreno Reséndiz, 1948 (Life Zone

ZOOGEOGRAPHY
Brattstrom, 1953 (Cactus and Reptiles), 1955 (Reptiles)
Brattstrom and Howell, 1956 (Birds)
Durham, 1947 (Corals)
Fraser, 1939, 1940 (Hydroids)
Garman, 1899 (Reptiles)
Garth, 1946b (Crabs)
Herre, 1940 (Fish)
Johnston, 1931 (Plants)

- Manter, 1940b (Parasites of fish)
- Myers, 1940 (Fish)
- Taki, 1940 (Chitons)
- Wallace, 1876 (Birds and Lizards)

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- GENERAL
  - Brandegee, 1898, 1900
  - Escuela Superior de Guerra, 1949
  - Gentry, 1949
  - Johnston, 1931
  - Medina G., 1957
  - Moreno Reséndiz, 1940
  - Pilsbry, 1898
  - Vasey and Rose, 1891
- ALGAE
  - Allen, 1933 (Phytoplankton)
  - Dawson, 1952, 1954, 1957
  - Drouet, 1936
  - Mann, 1907 (Diatoms)
  - Setchell, 1937
  - Setchell and Gardner, 1930, 1937
  - Taylor, 1945
- FUNGI
  - Bonar, 1939
  - Dodge, 1936 (Lichens)
  - Hendrick, 1942 (Lichens)
  - Linder, 1934 (Lichens)
- BRYOPHYTES
  - Clark, 1953
  - Howe, 1934
  - Steere, 1946
- ANGIOSPERMS
  - Brandegee, 1898, 1900
  - Brattstrom, 1953
  - Escuela Superior de Guerra, 1949
  - Gentry, 1949
  - Hitchcock, 1935
  - Johnston, 1931
  - Moreno Reséndiz, 1948
  - Pilsbry, 1898
  - Svenson, 1939
  - Vasey and Rose, 1891

ZOOLOGY

- INVERTEBRATES
  - *Protozoa-Foraminifera*
    - Cushman, 1932, 1933, 1942
    - Cushman and McCulloch, 1939, 1940, 1942, 1948, 1950
    - Lalicker and McCulloch, 1940
  - *Coelenterata*
    - Durham, 1947, 1950 (Corals)
    - Durham and Barnard, 1952 (Stony corals)
    - Fraser, 1938, 1939, 1940, 1948 (Hydroids)
  - *Bryozoa*
    - Osburn, 1950, 1952, 1953
  - *Annelida*
    - Fisher, 1952 (Sipunculids)
    - Hartman, 1939, 1940, 1941, 1944, 1946, 1947a, 1947b, 1950
    - Treadwell, 1937
  - *Mollusca*
    - Dall, 1900, 1909, 1926
    - Dall and Ochsner, 1928
    - Hanna and Strong, 1949
    - Hertlein, 1938
    - Hertlein and Strong, 1940, 1943, 1946a, 1946b, 1947, 1948, 1949a, 1949b, 1950 1951
    - Ingram, 1948
    - Medina G., 1957
    - Pilsbry, 1898
    - Rust, 1955
    - Soot-Ryen, 1955
    - Stearns, 1894
    - Strong and Hanna, 1930
    - Taki, 1940
  - *Arthropoda*
    - Crustacea
      - Barnard, 1954
      - Boone, 1927 (Brachyura)
      - Burkenroad, 1937, 1938, (Decapoda)
      - Crane, 1937, 1941, 1947 (Brachyura)
      - Escuela Superior de Guerra, 1949
      - Garth, 1940, 1946a, 1946b (Brachyura)
      - Giesbrecht, 1895 (Copepoda)
      - Holthuis, 1951, 1952 (Decapoda: Natantia)
      - Rathbun, 1924, 1937 (Brachyura)
      - Schmitt, 1940 (Stomatopoda)
      - Tattersall, 1951 (Mysidacea)

- Wilson, 1937, 1950 (Copepoda)
- Insecta
  - Heidemann, 1901 (Hemiptera)
  - Light, 1930, 1935 (Isoptera)
  - Medina G., 1957
  - Rehn, 1913 (Orthoptera)
  - Van Duzee, 1933 (Hemiptera), 1934 (Lepidoptera)
  - Wheeler, 1933 (Hymenoptera: Formicidae)
- *Echinodermata*
  - Clark, 1948
  - Deichmann, 1937, 1938, 1941
  - Ziesenhenne, 1937
- *Parasites*
  - Manter, 1940a, 1940b (Digenetic Trematodes)
  - Meserve, 1938 (Monogenetic Trematodes)
  - Van Cleave, 1940 (Acanthocephala)
  - Wilson, 1937, 1950 (Copepoda)

VERTEBRATES

- *Fish*
  - Beebe and Crane, 1947
  - Beebe and Pyl, 1944
  - Beebe and Tee-Van, 1941a, 1941b, 1941c
  - Brock, 1943
  - Escuela Superior de Guerra, 1949
  - Fowler, 1938, 1944
  - Gilbert, 1891a, 1891b, 1897
  - Heller and Snodgrass, 1903
  - Herre, 1940
  - Hubbs, 1953
  - Jordan and Evermann, 1896–1900
  - Jordan and Gilbert, 1881
  - Jordan and McGregor, 1898
  - Manter, 1940a, 1940b (Digenetic Trematodes from fish)
  - Medina G., 1957
  - Meek and Hildebrand, 1923–28
  - Meserve, 1938 (Monogenetic Trematodes from fish)
  - Myers, 1940
  - Orton, 1955
  - Schultz, *et al.*, 1953
  - Snodgrass and Heller, 1905
  - Tee-Van, 1940
  - Van Cleave, 1940 (Acanthocephala from fish)
  - Wilson, 1937, 1950 (Copepods from fish)
- *Reptiles*
  - Bogert and Oliver, 1945
  - Boulenger, 1885
  - Brattstrom, 1953, 1955
  - Burt and Myers, 1942
  - Cope, 1872, 1900
  - Garman, 1899
  - Hanna, 1925, 1926
  - Mittleman, 1942
  - Ortenburger, 1923, 1938
  - Pilsbry, 1898
  - Schmidt, 1922
  - Slevin, 1926, 1931
  - Stejneger, 1901
  - Tanner, 1944
  - Townsend, 1891b
  - Van Denburgh, 1895, 1905, 1922
  - Van Denburgh and Slevin, 1914
  - Wallace, 1876
- *Birds*
  - Anonymous, 1953b
  - Anthony, 1896a, 1896b, 1898a, 1898b, 1900
  - Bent, 1948
  - Blake, 1953
  - Brattstrom, 1953
  - Brattstrom and Howell, 1956
  - Brewster, 1903
  - Chapman and Griscom, 1924
  - Colnett, 1798
  - Friedmann, Griscom, and Moore, 1950
  - Gifford, 1913
  - Godman, 1907–10
  - Grayson, 1872
  - Grinnell, 1928
  - Hanna, 1926
  - Kaeding, 1905
  - Lamb, 1925
  - Lawrence, 1871
  - Loomis, 1918

McLellan, 1925, 1926
Meinertzhagen, 1926
Oberholser, 1898, 1904, 1917a, 1917b, 1917c, 1918
Pilsbry, 1898
Ridgway, 1883, 1884, 1887
Slevin, 1931
Snodgrass and Heller, 1902, 1904
Townsend, 1891a
Wallace, 1876
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Brattstrom, 1955
Escuela Superior de Guerra, 1949
Hanna, 1926
Medina G., 1957
Morrell, 1832
Orr, 1940
Richards, 1957a
Scammon, 1874
Scammon and Cope, 1869

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The Pole Tide[1]

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Abstract—About 10,000 mean monthly values of sea level from 11 tide stations have been analyzed by the method of Tukey to obtain the power spectra in the frequency range of 0.0125 to 6 cycles per year (cpy). The spectral density is on the order of 10^2 mm^2/cpy and is remarkably uniform over this frequency range, with the following exceptions: (i) a sharp rise at the low-frequency tail, from 10^2 mm^2/cpy at 0.1 cpy to 10^5 mm^2/cpy at 0.0125 cpy (presumably associated with variations in recorded sea level arising from continental unrest); (ii) the line spectrum associated with the annual variation and its harmonics; and (iii) a weak peak of 0.84 cpy, barely above noise level, which is identified with the 14-month 'pole tide' corresponding to the earth's free nutation (Chandler wobble). The average pole tide for all stations gives an amplitude twice that predicted by equilibrium theory. The contribution to the peak of the pole tide is largely from three localities: Swinemünde, Marseille, and a combined set of Netherlands stations. Apparently the pole tide is not in accord with equilibrium theory. This raises some questions concerning the interpretation of Love numbers as derived from the period of free nutation.

Introduction

Ever since Euler showed in 1765 that the earth should have a free nutation with a period of 10 months, there have been attempts to detect such a motion from precise measurements of latitude. In 1891 a variation in latitude was discovered by Chandler, but its period was 428 days instead of the expected 305 days. The explanation was soon given by *Newcomb* [1892]: Euler's theory applies to a rigid earth; for the actual case, the elastic yield of the solid earth and the fluid yield of the oceans have to be taken into account, and these increase the period of free nutation from 10 to 14 months. For a completely fluid earth a shift in the axis of rotation would result in complete adjustment of the figure to the new rotational potential, and no wobble would result; that is, the nutation period would be infinite.

The differential yield of earth and oceans produces a pole tide. To visualize this we consider the case of a rigid earth completely surrounded by an ocean of uniform depth. If the solid earth were turned 90° relative to the axis of rotation so that an equatorial radius coincided with the rotational pole, then the land would be up 20 km relative to the water along the earth's long axis and down 20 km along its short axis. Actually the wobble amounts to about 0.1″ instead of 90°, so that we might expect the pole tide to be on the order of

$$\frac{0.1''}{90^\circ\ 60^\circ\ 60} \times 20\ \text{km} = 6\ \text{mm}$$

The fact that the solid earth also yields when the axis of rotation shifts reduces the measurable tide to about one half of this value. The gravitational attraction of the tide itself (both water and earth) increases it by about one third. We end up with about 5 mm for the expected pole tide. A systematic derivation is given in the section entitled 'Theory.' The pole tide is unique among the tides in not being caused by the sun or the moon.

Tide records are read hourly to an accuracy of perhaps ±1 cm. The detection of a 5-mm

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Table 1—*Sea-level stations*

Group	Station	Location	Years of record
I	1	Swinemünde, Germany 54°N. 14°E.	1811–1943
	2	Netherlands, 52°N. 5°E. (average of 6 stations)*	1865–1951
	3	Brest, France 48°N. 4°W.	1807–1943
	4	Marseille, France (Marégraphe) 43°N. 5°E.	1885–1946
II	5	Buenos Aires, Argentina 35°S. 58°W.	1905–1946
	6	Baltimore, Maryland 39°N. 77°W.	1902–1955
III	7	Portland, Maine 44°N. 70°W.	1912–1955
	8	Seattle, Washington 48°N. 122°W.	1899–1955
IV	9	Wazima, Japan 37°N. 137°E.	1900–1949
	10	Hososima, Japan 32°N. 132°E.	1900–1949
V	11	Bombay, India 19°N. 73°E. (Apollo Bandar)	1878–1947

*Delzijl, Harlingen, Den Helder, Hoek van Holland, Hellevoetsluis, Vlissingen

pole tide depends then on one's hope that the errors are largely random, so that in the monthly averages of hourly values the errors are reduced by something like a factor $(30 \times 24)^{1/2} \approx 27$ as compared with the error in the hourly values. When we first decided to search tide records for the pole tide, we were not aware that others had been willing to speculate in so marginal an undertaking. The literature turns out to be remarkably large. The first mention of the problem appears to have been made by Lord Kelvin:[2] "The sea would be set into vibration, one ocean up and another down. . . ." The first harmonic analysis was made by *Christie* [1900]. *Bakhuysen* [1913] measured records of sea level at Amsterdam going back to 1700. Further analyses were made by *Przbyllok* [1919], *Baussan* [1951], and *Maksimov* [1954, 1956]. The procedure in all these analyses was to devide the data into as many 7-year series as possible and to derive for each series the amplitude and phase of the sixth harmonic, corresponding exactly to a 14-month period. All these attempts except Przbyllok's were reported as being successful in having established the existence of a pole tide. On the basis of the present study it turns out that the results would not have differed by a large factor if the investigators had searched for a period of 13 months, or 15 months. We have obtained the power spectrum of sea level as a continuous function of frequency. This involves no preconceived assumption as to the frequency of the pole tide and, furthermore, furnishes an estimate of the 'noise level' at adjoining frequencies. The noise level is very high, and the superimposed spectral peak of the pole tide is barely detectable.

Analysis

The analysis was performed with the aid of high-speed digital computers. The procedure follows closely the one adopted by *Munk, Snodgrass, and Tucker* (in press) in their study of low-frequency ocean waves; and this, in turn, is based on the work of *Blackman and Tukey* [1958]. The detection of weak signals in the presence of noise depends rather critically on the procedure, and in this section the vital parameters have been recorded. Subsequent discussions of the results and their interpretation can be read without reference to this section.

Observations—Mean monthly values of sea level at 11 locations (Table 1) were taken from the *Publications Scientifiques* of the Association d'Oceanographie Physique, Union Geodesique et Geophysique Internationale. Latitude observations consist of unsmoothed values of m_1 and m_2 (directional cosines of the pole of rotation, relative to its mean position, along Greenwich and 90° east of Greenwich) from the *International Latitude Service* for 1900–1954 [*Walker and Young*, 1957, Table 1*a*].

Prefiltering—Three types of numerical filters were applied to the raw data: (1) annual rejection (AR); (2) high-pass filtering (HP);

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[2] Presidential Address, 1876, Section of Mathematics and Physics, British Association for the Advancement of Science.

TABLE 2—*Computation parameters*

Station	Years	Least count	AR	HP	LP	Δt years	m	Δf (years)$^{-1}$	α	N	ν	95% confidence limits of energy	Figures
Swinemünde	1900–1943	1 mm	AR	12	...	1/12	48	1/8	8	502	20	0.6–2.1	1
Swinemünde	1900–1943	1 mm	AR	14	5	1/4	160	1/80	80	164	1.6	.2–100	1
Netherlands	1865–1951	1/6 mm	AR	12	...	1/12	48	1/8	0.22	1015	42	.7–1.7	1, 2
Netherlands	1865–1951	1/6 mm	AR	14	5	1/4	160	1/80	2.22	336	3.7	.4–9.0	1
Netherlands	1900–1951	1/6 mm	AR	12	...	1/12	48	1/8	0.22	598	24.	.6–1.9	1
Netherlands	1900–1951	1/6 mm	AR	14	5	1/4	160	1/80	2.22	196	1.9	.2–50	1
Latitude	1900–1954	0″.01	AR	...	5	1/4	160	1/80	80	218	2.7	.3–20	3

(3) low-pass filtering (LP). Annual rejection was accomplished for each station by subtracting from all January values the average January value and similarly for other months. This removes the seasonal variation and its harmonics; that is, periods of 12, 6, 4, 3, 2.4, and 2 months. The high-pass and low-pass filters are described by *Munk, Snodgrass, and Tucker* (in press), Sections 5.4 and 5.3. Half widths of the filters are given in Table 2.

The purpose of these operations is to suppress, prior to the analysis, certain parts of the spectrum which are not of primary concern in our study. The high-pass filter removes the secular drift in sea level; the low-pass filter smooths the record. If these features at the two extremes of the spectrum were not suppressed, they would appreciably contaminate the spectrum in the central frequencies. The annual term is particularly troublesome because it is so much larger than the pole tide (typically 20 cm as compared with 5 mm) and yet so close in frequency. Without prior removal the side bands of the strong annual line would bury the weak spectral line of the pole tide. At the completion of the spectral analysis a correction is made for the known response characteristics of the high- and low-pass filters. The plotted spectra are therefore complete as they stand, except for the omission of the seasonal line spectrum.

Power spectra—Figures 1, 2, and 3 show selected spectra. (Graphs of all spectra and a complete list of computation parameters are included in an unpublished dissertation [*Haubrich*, 1958]). Pertinent computation parameters are given in Table 2. Here Δt is the sampling interval; m is the number of spectral estimates in the frequency range of 0 to $m\ \Delta f$, where $\Delta f = (2\ m\ \Delta t)^{-1}$ is the frequency *resolution;* α is the scale factor in going from (least count)^2 to units of power density, mm^2/cpy; and N is the total number of values.

Each spectral estimate of the energy density is subject to random error. It can be shown that the estimates follow a 'chi-squared' probability distribution which depends on a parameter $\nu = 2N/m - 1/2$, 'the number of degrees of freedom.' ν and the associated 95 per cent confidence limits are given in Table 2 for each spectrum. There is thus a 95 per cent probability that the true value of the energy density lies within the stated proportion of the calculated values. For frequency bands composed of several lines the degrees of freedom are larger and the uncertainty limits are correspondingly narrower [*Blackman and Tukey*, 1958, Section 9].

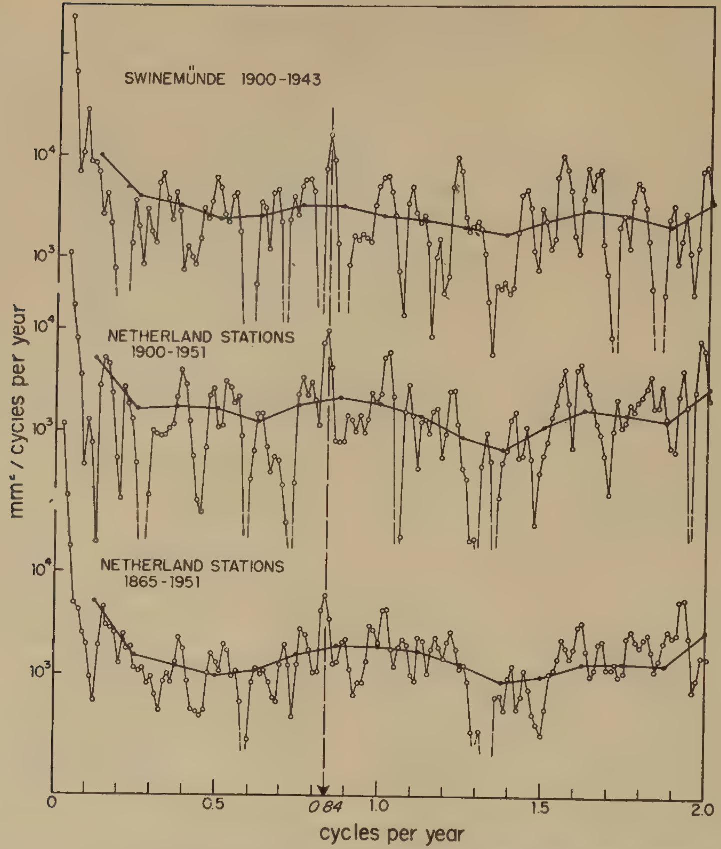

FIG. 1—Power spectra for Swinemünde and the Netherlands stations; solid circles, low-resolution spectra; open circles, high-resolution spectra.

The spectra are obtained by computing the cosine transforms of the autocorrelations. The result is a smoothed spectrum. As always, there are conflicting desires between high resolution (small Δf) and statistical reliability (large ν). For the low-resolution spectra ($\Delta f = 0.125$ cpy) there is appreciable smoothing; for the high-resolution spectra ($\Delta f = 0.0125$ cpy) there is little smoothing, and the uncertainty limits are very large. In the latter case we might as well have computed the power for each harmonic of the record, without resorting to autocorrelation. The method was used only because it was available in convenient machine-programed form.

Co- and quadrature-spectra—The equilibrium tide for each station was computed for each month from 1900 to 1954 according to (7), using the unsmoothed latitude data [*Walker and Young*, 1957, Table I*a*] and setting $1 + k - h = 0.68$ [Jeffreys, 1952, p. 206]. The values so obtained were analyzed with the recorded sea level to obtain the normalized co- and quadrature-spectra, P and Q (Fig. 4). If the recorded tide is in phase with and proportional to the equilibrium tide, then $P = 1$ and $Q = 0$ over the frequencies of the pole tide; if the recorded tide lags by 90°, then $P = 0$ and $Q = 1$.

THEORY

For a rigid earth the period of free nutation would be 10 months. But deformations are caused both in the solid earth and in the oceans

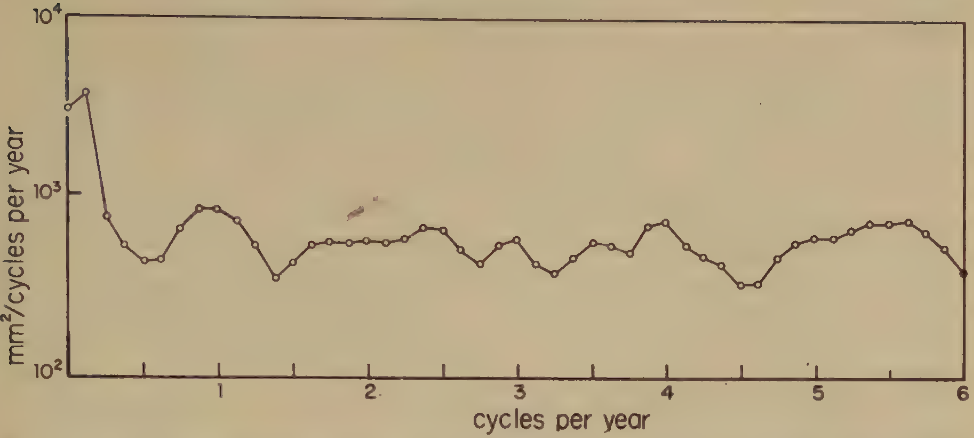

Fig. 2—Low-resolution spectrum for the Netherlands stations over the entire frequency range of analysis, from 0 to 6 cpy.

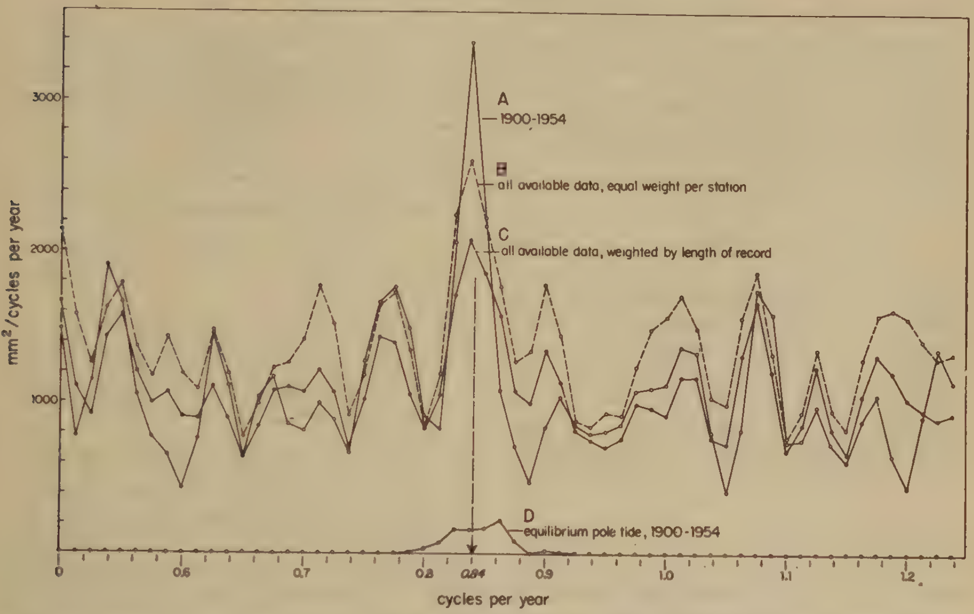

Fig. 3—Composite high-resolution spectra of the recorded ocean tides (*A, B, C*) and of the equilibrium pole tide (*D*).

by the potential disturbance associated with the nutation. As a consequence of these deformations the period is lengthened to the observed value of 14 months. In this section we inquire about the extent to which lengthening can be associated with deformation in the ocean. Upon subtraction of this oceanic effect, the rigidity of the solid earth can be derived and compared with values obtained from seismic data. We also estimate the ellipticity in the nutation brought about by the uneven distribution of land and sea.

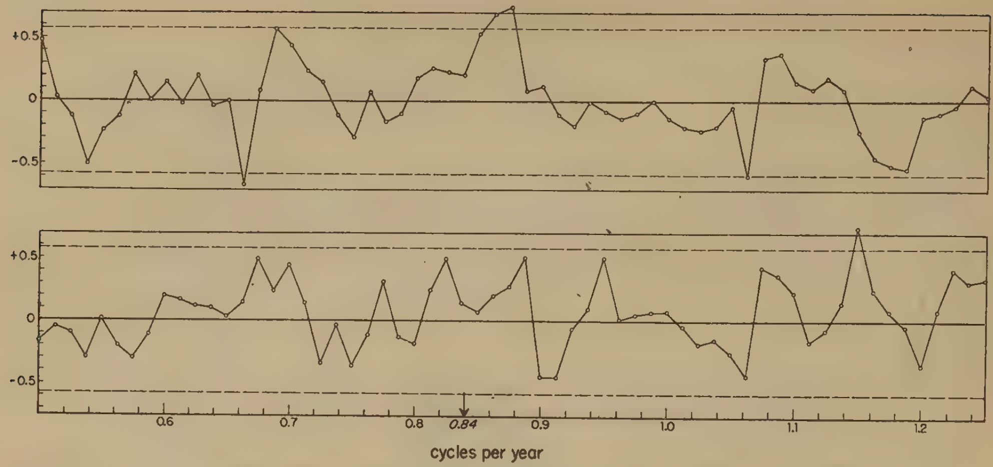

FIG. 4—Composite co-spectrum (top) and quadrature-spectrum (bottom) of the recorded ocean tide versus the equilibrium pole tide.

First, the effect of the water tide alone is considered. Deformation of the ocean bottom due to loading by the tide is then discussed. In this approximate treatment harmonics other than those of degree 2 have been ignored.

Products of inertia of the pole tide—The rotational potential is

$$U_0 = \tfrac{1}{2}\Omega^2 a^2 \sin^2\theta \qquad (1)$$

where Ω is the earth's rotational velocity, a its mean radius, and θ the colatitude. For small changes in θ the change in potential is given by

$$\delta U_0 = U = \Omega^2 a^2 \sin\theta\cos\theta\,\delta\theta$$

$$= -\Omega^2 a^2 \sin\theta\cos\theta(m_1 \cos\lambda + m_2\sin\lambda) \qquad (2)$$

where m_1 and m_2 are the direction cosines between the axis of rotation and the x_1-axis (toward Greenwich) and the x_2-axis (toward 90° east of Greenwich), respectively, and λ is east longitude.

As a result of this potential disturbance the sea bottom is raised by hU/g and the sea surface relative to the sea bottom by

$$\xi_0 = \frac{1+k-h}{g}U \qquad (3)$$

where g is gravity at the surface and k, h, the 'tidal-effective' Love numbers [*Jeffreys*, 1952, p. 204]. Due to the irregular distribution of oceans and continents, a correction tide $\xi'(t)$ (introduced by Sir George Darwin) must be added so that the total tide,

$$\xi(t, \theta, \lambda) = \xi_0(t, \theta, \lambda) + \xi'(t) \qquad (4)$$

is consistent with the conservation of mass

$$\int_{\text{oceans}} \xi\, ds = 0 \quad \text{and} \quad ds = \sin\theta\, d\theta\, d\lambda \qquad (5)$$

It is now convenient to define a function [*Munk and MacDonald*, 1960, Appendix]:

$$\begin{aligned} f(\theta, \lambda) &= 1 \text{ where there are oceans.} \\ f(\theta, \lambda) &= 0 \text{ where there are continents.} \end{aligned} \qquad (6)$$

Let a_n^m, b_n^m describe the coefficients of degree n and order m in an expansion of $f(\theta, \lambda)$ into spherical harmonics. These coefficients have been tabulated by Munk and MacDonald up to degree 8. Equation (4), subject to restraint (5), can now be written

$$\xi = -\frac{1+k-h}{g}\frac{\Omega^2 a^2}{2} \cdot\left\{m_1\left(\sin 2\theta\cos\lambda - \frac{a_2^1}{5a_0^0}\right) + m_2\left(\sin 2\theta\sin\lambda - \frac{b_2^1}{5a_0^0}\right)\right\} \qquad (7)$$

We shall need the products of inertia associated with the pole tide. These are

$$c_{13} = -a^4\rho \int_{\text{oceans}} \xi \sin\theta \cos\theta \cos\lambda \, ds = A(T_1 m_1 + R m_2) \tag{8}$$

$$c_{23} = -a^4\rho \int_{\text{oceans}} \xi \sin\theta \cos\theta \sin\lambda \, ds = A(T_2 m_2 + R m_1)$$

where ρ is the density of sea water, A, A, C are the earth's principal moments of inertia, and

$$\frac{R}{1+k-h} = \frac{4\pi\Omega^2\rho a^6}{Ag}\left[\frac{b_2{}^2}{35} + \frac{b_4{}^2}{63} - \frac{a_2{}^1 b_2{}^1}{100a_0{}^0}\right] = -0.11 \times 10^{-4}$$

$$\frac{T_1}{1+k-h} = \frac{4\pi\Omega^2\rho a^6}{Ag}\left[\left(\frac{a_0{}^0}{15} + \frac{a_2{}^0}{105} - \frac{4a_4{}^0}{315}\right) + \left(\frac{a_2{}^2}{35} + \frac{a_4{}^2}{63}\right) - \frac{(a_2{}^1)^2}{100a_0{}^0}\right] = 3.36 \times 10^{-4} \tag{9}$$

$$\frac{T_2}{1+k-h} = \frac{4\pi\Omega^2\rho a^6}{Ag}\left[\left(\frac{a_0{}^0}{15} + \frac{a_2{}^0}{105} - \frac{4a_4{}^0}{315}\right) - \left(\frac{a_2{}^2}{35} + \frac{a_4{}^2}{63}\right) - \frac{(b_2{}^1)^2}{100a_0{}^0}\right] = 2.16 \times 10^{-4}$$

to which we add, for future reference

$$S = \frac{8\pi}{15}\left(a_0{}^0 + \frac{1}{7}a_2{}^0 - \frac{4}{21}a_4{}^0\right) - \frac{4\pi}{100a_0{}^0}\left[(a_2{}^1)^2 + (b_2{}^1)^2\right] = 1.20$$

The equations of motion of the rotation pole are [*Munk and MacDonald*, 1960, 6.1.2]

$$\begin{aligned} dm_1/dt + \sigma_e m_2 &= \sigma_r c_{13}/(C - A) \\ dm_2/dt - \sigma_e m_1 &= -\sigma_r c_{23}/(C - A) \end{aligned} \tag{10}$$

where $\sigma_r = \Omega(C - A)/A$ is the frequency of nutation if the earth is rigid, and σ_e is the frequency which allows for the deformation of the solid earth but not of the oceans. The observed frequency σ is to be determined for a solution to (10). Making use of (7), (8), and (9), we can now put the equations of motion in the form

$$\begin{aligned} \frac{dm_1}{dt} + (\sigma_e - T_2\Omega)m_2 - R\Omega m_1 &= 0 \\ \frac{dm_2}{dt} - (\sigma_e - T_1\Omega)m_1 + R\Omega m_2 &= 0 \end{aligned} \tag{11}$$

with the solutions

$$m_1 = M_1 \cos\sigma t$$

and

$$m_2 = M_2 \sin(\sigma t + \beta) \tag{12}$$

provided that

$$\sigma^2 = \sigma_e{}^2 - (T_1 + T_2)\Omega\sigma_e - (R^2 - T_1T_2)\Omega^2 \tag{13}$$

$$\tan\beta = -\frac{\Omega R}{\sigma} \tag{14}$$

$$\frac{M_1{}^2}{M_2{}^2} = \frac{\sigma_e - T_2\Omega}{\sigma_e - T_1\Omega} \tag{15}$$

We note that $R \ll T_1$, $R \ll T_2$; furthermore $T_1\Omega/\sigma_e$ and $T_2\Omega/\sigma_e$ are small numbers. Accordingly,

$$\sigma = \sigma_e - \tfrac{1}{2}(T_1 + T_2)\Omega + \text{order } (T_1\Omega/\sigma_e)^2 \tag{16}$$

The observed frequency of nutation is $\sigma = \Omega/437$. For the usually accepted value, $1 + k - h = 0.68$ [*Jeffreys*, 1952, p. 206], this gives

$$\sigma_e = \Omega/404 \tag{17}$$

so that the oceans increase the period from 404 days to 437 days.

Love numbers for the solid earth—In any geophysical application we are not concerned with the nutation frequency for an earth without oceans but rather with the Love numbers associated with the solid portion of the earth. The relation between the observed frequency of nutation and the Love number k can be put into the form [*Munk and MacDonald*, 1960, 6.2.6 and 5.3.2]

$$\sigma = \sigma_r \frac{k_f - k}{k_f} \tag{18}$$

where

$$k_f = \frac{3G(C - A)}{a^5\Omega^2} = 0.96 \tag{19}$$

is the 'fluid' Love number, and G is the gravitational constant. Similarly, the frequency σ_e for an earth without oceans can be related to a Love number k_e according to

$$\sigma_e = \sigma_r \frac{k_f - k_e}{k_f} \tag{20}$$

We define

$$k_w = \tfrac{1}{2}k_f(T_1 + T_2)\frac{\Omega}{\sigma_r} = \frac{9}{8\pi}(1 + k - h)S\frac{\rho}{\bar{\rho}} \qquad (21)$$

where $\bar{\rho}$ is the mean density of the earth. Equation (16) can be written in either of the forms

$$\sigma = \sigma_e - \frac{k_w}{k_f}\sigma_r \qquad (22)$$

or

$$k = k_e + \frac{9}{8\pi}(1 + k - h)S\frac{\rho}{\bar{\rho}} = k_e + k_w \qquad (23)$$

Thus k_w as defined is that part of the Love number k which is due to the oceanic pole tide.

The problem is to evaluate k_e. We may regard $k = 0.29$ as known from the frequency of the Chandler wobble. We have followed two procedures: (a) Consider $(1 + k - h) = 0.68$ as known. Then it follows directly from (22) and (23) that

$$\frac{\Omega}{\sigma_e} = 404, \qquad h = 0.610, \qquad k_e = 0.235, \quad \text{and} \quad k_w = 0.055 \qquad (24)$$

Procedure (b) is based on a relation

$$h = (h_f/k_f)k_e = 2.05\, k_e \qquad (25)$$

for the 'equivalent Earth' [*Munk and MacDonald*, 1960, 5.6.2], where h_eU/g is the deformation of the solid earth corresponding to the potential k_eU. For the case of no loading, $h = h_e$. According to (25) the ratio h_e/k_e depends only on the density distribution and not on rigidity. Equations (22) and (23) with $h = 2.05\, k_e$ give

$$\frac{\Omega}{\sigma_e} = 396, \qquad h = 0.457, \qquad k_e = 0.223, \quad \text{and} \quad k_w = 0.069 \qquad (26)$$

Asymptotic cases—It is instructive to compare these results with various asymptotic models of oceans and the earth. For the case $\rho = 0$, we have $k_w = 0$, so that $\sigma = \sigma_e$, which is the appropriate frequency for an earth without oceans. For a rigid earth ($k_e = 0$, $h = 0$) completely surrounded by oceans, $S = 8\pi/15$ and

$$k_w = k = \frac{1}{(5/3)(\bar{\rho}/\rho) - 1} \qquad (27)$$

and

$$\sigma = \sigma_r\left(1 - \frac{k}{k_f}\right)$$

If the earth is homogeneous, $k_f = 3/2$. Thus, as the ocean density approaches the mean density of the earth, $\rho \to \bar{\rho}$, we find $\sigma \to 0$; the rotational axis becomes unstable. For the actual density distribution $k_f = 0.96$, so that instability is reached when $\rho = 4.5$ g cm^{-3}.

Ellipticity—The pole of rotation describes an ellipse

$$m_1^2 - (2\sin\beta\, M_1/M_2)m_1m_2 + (M_1/M_2)^2 m_2^2 = M_1^2\cos^2\beta \qquad (28)$$

The major axis (T_2 being less than T_1) points toward east longitude λ_0, where

$$\tan 2\lambda_0 = 2R/(T_1 - T_2) = -0.20 \quad \text{and} \quad \lambda_0 = -6^\circ \qquad (29)$$

Since β is small, (28) may be written to a good approximation

$$m_1^2/M_1^2 + m_2^2/M_2^2 = 1 \qquad (30)$$

The ellipticity is

$$\epsilon = 1 - \frac{M_2}{M_1} = 1 - \frac{\sigma_e - T_1\Omega}{\sigma_e - T_2\Omega} = 0.017 \qquad (31)$$

For comparison, the ratio of the amplitudes of m_1 amd m_2 was taken from the analysis of the unsmoothed latitude data, 1899 to 1954 [*Walker and Young*, 1957, Table Ia]. The result is

$$\epsilon = 1 - M_2/M_1 = 0.01 \pm 0.05 \qquad (32)$$

M_1 and M_2 are so nearly equal that the statistical error in the analysis of the latitude data gives a large uncertainty in the observed value of ϵ. But, as far as it goes, there is no inconsistency with the computed value (31). *Fedorov* [1949] derived a computed value of ϵ by a method similar to ours but stated that this value did not agree with the observed ellipticity of free nutation.

But the distribution of ocean and continents is not the only source of an ellipticity of the

Chandler wobble. In the first two decades of this century there was much discussion of the triaxiality of the earth, a discussion which is likely to be resumed in the light of the satellite observations. A difference in the equatorial moments of inertia will produce an ellipticity of the pole path. From geodetic measurements *Helmert* [1915] found

$$\frac{B - A}{C - \frac{1}{2}(A + B)} = \frac{1}{46} \qquad (33)$$

which corresponds to a difference of 230 meters between the equatorial semi-axes; the major axis is along 107°W. *Schweydar* [1916] found that the ratio (33) would produce an ellipticity $\epsilon = 0.016$. *Lambert* [1922] attempted to evaluate the ellipticity from different six-year series of latitude observations, 1900 to 1917. His values of ϵ range from 0.02 to 0.20, and the direction of the major axis from 59°W to 116°W.

If we can accept Helmert's values, it follows that the ellipticity in the wobble produced by the oceans is of the same order as that produced by the ellipticity of the equator, but oriented at right angles to it. A comparison of these results with observations is meaningless because of the larger uncertainty in the observed eccentricity.

Load deformation—The derivation so far neglects the load deformation of the solid earth associated with the oceanic pole tide. When this is taken into account, the ocean effect is reduced by about one seventh. In the following approximate treatment we write

$$k = k_s + k_w + k_w' \quad \text{and} \quad h = h_s + h_w' \quad (34)$$

where $h_w'U/g$ is the deformation of the sea bottom due to loading by the pole tide, and $k_w'U$ is the potential of the load deformation. With these definitions k_w, k_s, and h_s will have values somewhat different from those given in the previous sections.

The problem is to derive k_w', h_w' in terms of the other Love numbers. There are two opposing effects. The gravitational attraction by the pole tide on the earth lifts the earth by $h_s(k_wU)/g$, and this deformation is associated with a potential $k_s(k_wU)$. The pressure exerted by the pole tide on the earth depresses the earth, and this deformation is associated with a potential $-k_s(\rho/\bar{\rho})g\xi$ [*Munk and MacDonald*, 1960, Section 5.8]. The combined effect can be expressed in terms of the 'load Love numbers,'

$$k_w' = -\tfrac{2}{3}k_w h_s \quad \text{and} \quad h_w' = -\tfrac{2}{3}k_w h_s \qquad (35)$$

To include the effect of loading, we write

$$k_w + k_w' = \frac{9S}{8\pi}\frac{\rho}{\bar{\rho}}\left[(1 + k - h) + (\bar{\rho}/\rho)h_w'\right] \qquad (36)$$

in analogy with (21). The first part in the bracket is associated with the pole tide, the second part with the displacement of the sea bottom. The factor $(\bar{\rho}/\rho)$ allows for the greater density of the sea bottom.

With k considered to be determined by the observed Chandler frequency, (34), (35), and (36) give five relations between the six unknowns, h, h_s, k_s, h_w', k_w', k_w. Again we have obtained numerical solutions by the following two procedures: (a) Consider the relation $1 + k - h = 0.68$ as given; (b) assume $h_s = 2.05\, k_s$ according to the equivalent earth model (25). The results are

$$\begin{aligned} &\text{(a)} \quad \Omega/\sigma_s = 409, \; h = 0.61, \; h_s = 0.633, \\ &\qquad\qquad k_s = 0.245, \; k_w = 0.054 \\ &\text{(b)} \quad \Omega/\sigma_s = 402, \; h = 0.46, \; h_s = 0.476, \\ &\qquad\qquad k_s = 0.232, \; k_w = 0.061 \end{aligned} \qquad (37)$$

The lengthening of the nutational period which is attributable to the ocean equals (a) 28 days, (b) 35 days for the two models under consideration. Model (b)) gives a value of $1 + k - h = 0.83$, which is larger than the generally accepted value of 0.68. Neglecting load deformation, we previously obtained (a) 33 days, (b) 41 days. The effect of load deformation is then to reduce somewhat the effect of the oceanic pole tide.

Previous investigations—Estimates of the ocean effect on Chandler frequency using static theory have been made by *Larmor* [1915], *Rosenhead* [1929], *Fedorov* [1949], and *Jeffreys and Vicente* [1957b]. Larmor, using a homogenous earth model, found $k_s = 0.231$ after allowing for the distribution of oceans and continents. He estimated[3] that loading would reduce the ocean effect upon frequency by about 20 or 30 per cent. Rosenhead, using a two-layer earth composed of core and mantle, obtained k_e = 0.346 for the earth without oceans and k = 0.435 with oceans included.[4] The value $k = 0.435$ is far too high to be consistent with the Chandler frequency. Fedorov calculated the effect of oceans, taking into account their distribution but not including loading. Taking $1 + k - h = 0.70$ he obtained $k_e = 0.23$.

Takeuchi [1951] calculated the Love numbers for an earth without oceans and made comparisons with observed values obtained from the Chandler wobble. Using a statical theory of core and mantle he took an earth model based upon the seismic studies of K. E. Bullen and obtained

$$k_e = 0.3067 \quad h_e = 0.6186 \quad l = 0.083$$

for an outermost mantle density of 3.3. Finding the Love numbers, k in particular, to be highly dependent on surface density, Takeuchi also computed the Love numbers for a surface density of 2.7, obtaining

$$k_e = 0.256 \quad h_e = 0.594 \quad \iota = 0.080$$

Jeffreys and Vicente [1957*b*], using Takeuchi's solution for the mantle and a dynamic theory of the core, obtained a Chandler period of 392 days corresponding to $k_e = 0.208$. Adding the oceans to a homogenous earth with rigidity corresponding to $k_e = 0.208$, they arrived at the observed Chandler period after assuming the effect to be two thirds of that which would be produced by a complete ocean. This model allows for loading but contains the relation $h_e = 5/3\, k_e$, which holds only for a homogenous earth.

Discussion

Equation (7) permits us to compute the 'equilibrium pole tide' from astronomic observations of latitude. This has been done for each station for the years 1900 to 1954 using $1 + k - h = 0.68$. The equilibrium pole tide is proportional to $1 + k - h$ and therefore subject to the same uncertainty as the value of $1 + k - h$. An estimate of the uncertainty in $1 + k - h$ is by no means straightforward, as will be apparent from the preceding section. We estimate that the factor is known within an accuracy of ±20 per cent.

Figures 1 and 2 show some sample spectra of the tide records at individual stations. The spectra from the 11 tide-gage stations have been averaged, frequency band by frequency band, using different weight factors (spectra A, B, C, Table 3, Figure 3). Spectrum D is a similar average of the equilibrium pole tide at the 11 stations. If the sea level obeyed equilibrium theory, then the recorded spectrum A and equilibrium spectrum D would be identical. We shall discuss four features of the spectral peak near 0.84 cpy: frequency, phase, amplitude, and width.

Frequency—The three composite pole-tide spectra all show a peak very near 0.84 cpy, corresponding to a period of 1.19 years. The periods given in Table 3 have been calculated by taking the mean frequency of each of the spectral highs (equal energy to both sides of the mean frequency). For spectrum A the value is 1.194 years. From latitude observations the period of the Chandler wobble has been estimated at 1.195 ±0.015 years. The results from the oceanographic and astronomic observations are compatible.

Phase—Figure 4 shows the values of $P(f)$ and $Q(f)$, the normalized co- and quadrature-spectra for the pole tide versus equilibrium tide, averaged over 11 stations for frequencies f, from 0.50 to 1.25 cpy. A result $P(f) = +1$, $Q(f) = 0$ means that at frequency f there is a zero phase *difference* between the records: the phase itself can be random. For ν degrees of freedom, the 95 per cent confidence limits have been estimated at $\pm 2\nu^{-1/2}$, as shown by the dashed lines. There is a barely significant co-spectrum at a frequency just above the Chand-

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[3] Larmor obtained $h/a = \frac{1}{2}\Omega^2 a/g$ for the equilibrium rotational deformation of the oceans at the equator. This neglects the self potential of the water bulge. On the following page an erroneous factor of 2 is introduced which partially compensates for the first effect.

[4] After correction for an error in determining the Love number h (Rosenhead's equations 5.1 and 5.5). Rosenhead's published value, $k = 0.270$, would imply that the oceans *increase* the tidal-effective rigidity.

TABLE 3—*Composite spectra*

	Pole tide period, years	Total energy at 14 months peak, mm²	Noise energy, mm²	Pole tide energy, mm²	Amplitude, mm	Total degrees of freedom, ν	80% confidence limits of pole tide energy
A: 1900–1954	1.194	96.13	37.73	58.40	10.8	48	38.2–90.1
B: All years equal weight per station	1.187	90.51	52.40	38.11	8.7	145	25.8–54.4
C: All years stations weighted according to years of record	1.188	110.01	66.05	43.96	9.4	145	29.0–63.8
D: 1900–1954, equilibrium tides	1.182	12.10	0.4	11.70	4.8	12	7.2–24.0

ler frequency, and none at other frequencies. The result may perhaps indicate a tendency toward an in-phase relation between recorded and equilibrium pole tides, but the more important conclusion is that the phase relation is very poor. Swinemünde and the Netherlands stations have a peak in coherence over the Chandler frequencies, and this turns out to be consistent with a zero phase difference [*Haubrich*, 1958].

Amplitude—We have noted that the composite spectra have a peak at the Chandler frequency. Concerning the amplitude of the peak, two features are noteworthy: (i) There are striking differences from one station to the next. Three stations, Swinemünde, Marseille, and the Netherlands show definite peaks at essentially the same frequency, all having energy densities higher than anything on the record except the low-frequency 'drift.' At Bombay there is a peak at 0.84 cpy, but the height is not above the surrounding noise. The remaining seven stations do not show a distinct peak. (ii) The more recent data are characterized by a higher and sharper spectral peak. This is due, in part, to the higher 'noise level' of the older spectra. During the 19th century most of the sea-level stations used the tide pole, which was apparently not suitable for measuring the pole tide, whereas the more recent data are from recording tide meters. But even after allowing for the higher noise level, the composite spectra *B* and *C* (which include data from the 19th century) have less energy in the 14-month peak than spectrum *A*. The difference lies within the uncertainty of the results, but it might indicate a smaller average wobble in the 19th century than in the 20th. There is no way of checking this against latitude observations, inasmuch as these do not go back as far as the tide observations. The difference between older and newer sea-level spectra is apparent also for the Netherlands (Fig. 1), Marseille, and Swinemünde. In fact, in the 1811–1906 spectrum for Swinemünde (not shown) there is no significant peak near 0.84 cpy.

If the pole tide obeyed equilibrium theory with $1 + k - h = 0.68$, then spectra *A* and *D* should agree except for experimental noise. In fact, the observed pole tide (spectrum *A*) has far more energy than spectrum *D*. After subtracting a general noise level of 1000 mm²/cpy, the pole-tide energy is found to be four times the equilibrium value; accordingly the amplitude ratio is 2:1. From the 80 per cent confidence limits given in Table 3, there is a 10 per cent probability that the pole tide has an energy below 38 mm² and an equal probability that the equilibrium tide has an energy above 24 mm². The probability that the statistical instability of the spectra can account for the discrepancy between A and D is less than 1 per cent.

Maksimov [1954, 1956] has formed 180 seven-year series from 74 stations. From each of these he obtains by Fourier analysis the amplitude and phase of the sixth harmonic corresponding exactly to a 14-month period. No adjoining frequency was investigated, and this removes the possibility of estimating the extent to which noise may affect the results. Maksimov's final averages are 28.4 mm for the observed amplitude and 4.3 mm for equilibrium amplitudes, all referred to $\theta = 35°$. Our averages are 10.8 mm and 4.8 mm without latitude correction, but allowance is made for adjoining noise level. In our analyses the mean noise level in the vicinity of the Chandler frequency ranges from about 400 to 2500 mm^2/cpy, depending on the station. For an average station with a mean noise level of 1000 mm^2/cpy, the method used by Maksimov would give an amplitude of 12 mm for the noise alone. This is comparable to his mean observed amplitude (before introducing a latitude factor) of 14.4 mm. We conclude that Maksimov's large value is due principally to noise. Analyses by the same method were made on atmospheric pressure [*Maksimov*, 1954]. One might suspect that noise would affect these results in a similar manner.

Width of spectral peak—The sharpness of the spectral peak can be related to the damping of the free nutation. We can see in Figure 3 a remarkable discrepancy between the widths of observed and equilibrium spectra. The observed spectrum appears to involve three adjoining frequencies, and this is just the expected signature of the Tukey method for a spectral line, or at least a peak that is narrow compared with the spectral resolution $\Delta f = 0.0125$ cpy. The spectrum of the equilibrium pole tide extends over many adjoining frequency bands. A convenient dimensionless parameter for portraying the spectral width is the Q. For the equilibrium pole tide, estimates of Q range from 20 to 40, corresponding to damping times of 7.6 to 15.2 years. If our supposition of a sharp spectral peak is correct, the pole tide indicates a Q in excess of 100 and a damping time of more than 38 years.

This is a most surprising result. One can hardly conceive that the ocean has a sharp resonant peak at just this frequency; this would be a most unlikely coincidence and would require a degree of resonance not otherwise found in oceanic oscillations. At one time we suspected that the latitude peak was artificially broadened by nonlinear imperfections in observational technique and data reduction. This would favor oceanographic observations over astronomic observations, an appealing conclusion for geophysicists. But it is odd, to say the least, that the adjoining noise level in the astronomic measurements should be so much lower than that for oceanographic measurements.

At the suggestion of Tukey we undertook an analysis of variance to test the significance of the indicated sharpness of the pole-tide peak. Details are given in the Appendix. We investigated the probability of two alternatives: (i) a sharp (as seen through the Tukey filter) spectral peak at 0.84 cpy; (ii) a spectral width compatible with the latitude observations. For stations in group I (Table 1) the first alternative is more probable, but barely so. For the remaining groups the reverse is true. It would appear that a discussion of spectral width is not profitable with the material at hand.

Other analyses—We have computed the spectrum of mean monthly averages of the water level of Lake Michigan at Milwaukee from 1860 to 1958. There is no indication of a pole-tide peak. The noise level at this frequency is 10^3 mm^2/cpy, which is equal to corresponding values in the open sea.

We have also computed the spectrum of the average tide record (rather than the average of the spectra of individual records, Figs. 3 and 4). This was done as follows: Suppose that $m_1(t)$, $m_2(t)$ are the positions (at times t) of the 'pole-tide pole' to be determined from the recorded tide levels $\xi_i(t)$ at station i. Let

$$a_i = \sin\theta_i \cos\theta_i \cos\lambda_i$$

and

$$b_i = \sin\theta_i \cos\theta_i \sin\lambda_i$$

be coefficients depending only on the positions of the station. By making

$$\sum_{i=1}^{N} [a_i m_1(t) + b_i m_2(t) + z(t) - \xi_i(t)]^2$$

as small as possible, $m_1(t)$, $m_2(t)$ and the 'Kimura term' $z(t)$ are determined [*Munk and MacDonald*, 1960, Section 7.3]. If the pole-tide pole obeyed an equilibrium hypothesis, then the spectrum of the components of the pole-tide pole should be associated with a better signal-to-noise ratio than the average spectrum. In fact, the spectra gave no indication of a 14-month peak.

The background spectra—The spectra of all records rise sharply at the low-frequency end, commencing at about 0.1 cpy. The most obvious interpretation is that we are dealing with a superposition of two separate spectra (apart from the Chandler peak and seasonal line spectrum): (i) a white noise on the order of 10^3 mm^2/cpy; (ii) a low-frequency peak, diminishing from 10^5 mm^2/cpy at 0.01 cpy to 10^3 mm^2 at 0.1 cpy and presumably dropping beneath the white noise at higher frequencies. The two spectral features are presumably associated with different geophysical phenomena, but this is by no means proven.

The white noise is probably due to meteorologically induced fluctuations in sea level. Two possible causes suggest themselves for the low-frequency rise: climatically induced changes in world-wide sea level or the effect of vertical movements of contents. We believe the second alternative to be the more likely. World-wide changes in sea level would be coherent from station to station and in phase. In fact the cross-spectra between Bombay and Swinemünde [*Haubrich*, 1958] are out of phase at the lower frequencies. *Munk and Revelle* [1952] plotted decade-to-decade variations in sea level for all available tide stations, and it turns out that these decade averages are indeed incoherent.

The total power contained by the low-frequency tail is on the order of 50 cm^2. Suppose we set $\xi = kt$, corresponding to a linear rise in water level (or drop in beach level). We set the mean elevation equal to zero. The mean-square elevation for T years of record is then $k^2T^2/12 = 50$ cm^2. With $T = 50$ years this gives $k = 0.25$ cm year^{-2}, which is of the right order.

CONCLUSIONS

The composite spectra indicate a pole tide, the frequency of which is in good agreement with that obtained from latitude observations. There are a number of puzzling features. The pole tide appears at only four of the eleven stations investigated, and at these stations it is considerably larger than the corresponding equilibrium values. Spectra of the pole-tide pole (which assumes a dependence on latitude and longitude in accordance with equilibrium theory) do not indicate the pole tide at all! Apparently the pole tide does not support an equilibrium hypothesis.

Offhand, this would appear to be an implausible situation. It is known that the fortnightly tide does not deviate radically from equilibrium; accordingly, the 14-month tide, being of longer period, could be expected to agree very closely with equilibrium theory. But this is not a valid extrapolation. The fortnightly tide is a p_2^0 spherical harmonic, the pole tide a p_2^1 harmonic. In the former case the axis of the tidal oscillation remains fixed; in the latter case it does not. The theoretical developments are quite different for the two cases, and we cannot judge whether the dynamic effects on the pole tide are negligible. In the case of the core, *Jeffreys and Vicente* [1957*a*, *b*] have demonstrated that the dynamic effects are important in treating the free nutation.

If the equilibrium argument is not valid and the amplitude of the pole tide varies erratically from place to place, then the analysis of variance as outlined in the Appendix is not pertinent. (We have taken the same B for all stations.) The evidence in favor of the relatively broad spectral peak of the pole tide may not be decisive.

There are difficulties in comparing the tidal-effective Love number k of the planet earth (derived from the period of free nutation) with the corresponding number k_s for the solid earth (derived from seismic observations). These two numbers have often been set equal. The usually quoted value is 0.29. But there should be a difference because of the effects of the oceans and the fluid core. According to Jeffreys and Vicente the effect of the core is to increase k by roughly 20 per cent; the pole tide leads to a reduction by roughly the same amount, equation (37), and the two effects just happen to cancel, provided the pole tide follows the equilibrium law. If this is not the case, then at present there is no way to compare k and k_s.

TABLE 4—*Values of log P_{ij}*

		j																						
Station, i	α_i	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78
1	0.2263	0.11	3.36	3.59	3.40	3.70	3.76	3.77	3.65	2.40	0.13	3.87	4.20	3.96	3.12	2.07	0.18	2.92	3.21	3.16	3.22	3.19	3.15	3.50
2	.2356	2.47	2.10	0.56	2.49	3.37	3.53	3.36	3.49	3.31	3.06	3.87	4.00	3.62	2.90	2.90	2.91	3.16	3.12	3.00	3.16	2.98	3.13	3.39
3	.2471	3.56	3.59	3.01	2.56	2.78	3.18	3.65	3.56	3.07	2.84	1.83	1.68	1.44	0.16	2.79	2.74	2.53	3.17	3.00	2.77	3.39	3.36	3.24
4	.2485	1.31	2.71	2.94	2.93	2.83	2.67	2.64	2.82	3.06	2.84	3.39	3.77	3.59	3.00	2.81	0.18	2.31	3.14	3.05	2.64	2.85	2.77	2.68
5	.2210	3.01	2.09	0.11	2.96	3.55	3.68	3.49	3.25	3.29	2.98	2.14	2.95	2.91	2.83	3.15	3.10	2.58	0.19	0.20	0.21	0.21	1.21	1.52
6	.2388	2.53	2.73	2.69	2.31	1.80	1.72	2.24	2.51	2.18	1.36	2.47	2.49	2.93	3.23	2.94	1.14	1.54	2.29	2.86	3.17	3.07	2.57	2.50
7	.2497	1.08	1.08	1.08	0.88	2.37	2.73	2.89	2.84	2.73	2.90	3.21	3.09	2.45	3.04	3.05	2.08	1.15	2.43	2.87	2.76	2.21	2.78	2.76
8	.2471	3.08	3.07	2.52	1.08	1.79	2.72	3.02	2.89	3.23	3.37	3.14	3.14	3.22	3.05	2.32	3.16	3.50	3.30	2.83	2.46	2.54	3.03	3.04
9	.2314	3.01	2.70	2.75	2.41	2.94	2.99	2.53	1.99	3.00	3.29	2.99	2.87	3.30	3.27	2.85	2.75	3.03	2.88	2.80	2.88	2.40	2.91	3.18
10	.2020	3.04	3.06	3.34	3.17	2.22	2.29	2.98	2.94	2.11	2.11	2.46	2.61	3.08	3.31	3.12	2.03	2.35	3.15	3.23	2.85	2.42	2.66	2.63
11	.0951	2.52	2.85	2.58	2.64	2.67	2.06	1.48	1.73	2.00	2.59	2.86	2.77	2.68	2.47	1.14	2.50	3.11	3.02	2.52	2.92	3.03	2.61	2.14
I	.2394	2.98	3.23	3.17	3.01	3.35	3.46	3.52	3.48	3.06	2.80	3.65	3.91	3.64	2.90	2.73	2.53	2.86	3.16	3.06	3.02	3.15	3.15	3.30
II	.2299	2.84	2.51	2.37	2.76	3.27	3.40	3.23	3.03	3.04	2.71	2.33	2.79	2.92	3.07	3.06	2.82	2.33	1.98	2.54	2.85	2.75	2.27	2.30
III	.2484	2.79	2.78	2.24	1.00	2.17	2.73	2.96	2.87	3.05	3.20	3.19	3.12	2.99	3.05	2.82	2.90	3.20	3.06	2.85	2.63	2.41	2.92	2.92
IV	.2167	3.03	2.93	3.16	2.96	2.69	2.75	2.82	2.71	2.73	2.99	2.78	2.75	3.20	3.29	3.01	2.49	2.79	3.05	3.08	2.86	2.41	2.79	2.97
V	.0951	2.52	2.85	2.58	2.64	2.67	2.06	1.48	1.73	2.00	2.59	2.86	2.77	2.68	2.47	1.15	2.50	3.11	3.02	2.52	2.92	3.03	2.61	2.14
S_j'		10	19	18	26	11	22	32	115	427	700	1585	1950	2138	2318	726	2	328	169	42	34	90	57	36
S_j''		0	0	0	0	0	0	0	0	0	0	.25	.50	.25	0	0	0	0	0	0	0	0	0	0

Acknowledgments—We are greatly indebted to John Tukey for his frequent advice concerning the analysis of variance.

APPENDIX

Table 4 contains a double-entry listing of $\log P_{ij}$ where P_{ij} is the computed power density of the spectrum for station i (Table 1) at frequency $j\Delta f$, $\Delta f = 0.0125$ cpy. We let σ_i^2 designate the average power density to both sides of the pole-tide peak. We wish to fit the computed spectral densities to some scheme

$$P_{ij} = \sigma_i^2 + B\alpha_i S_j = \sigma_i^2\left(1 + \frac{B\alpha_i S_j}{\sigma_i^2}\right)$$

so that

$$\log P_{ij} = A_i + \frac{B_0\alpha_i S_j}{\sigma_i^2}$$

to a first order, and

$$\log P_{ij} = A_i + \frac{B\alpha_i S_j}{\sigma_i^2} - \frac{1}{2}\left(\frac{B_0\alpha_i S_j}{\sigma_i^2}\right)^2$$

to a second order. Here $\alpha_i = \sin^2\theta_i \cos^2\theta_i$ is the equilibrium scale factor depending on the colatitude of the station.

We wish to distinguish between two alternatives: (i) $S_j = S_j'$, the power density of the latitude data and (ii) $S_j = S_j''$, the spectrum for a sharp peak at $j = 67$. Values of S_j' and S_j'' are given in Table 4. Included in the former alternative is the presumption that the spectra of the observed tide correspond to the computed latitude spectra; in the second alternative, they correspond to a spectral line at 0.84 cpy.

The following regression schemes are fitted by least squares

$$W_0' = \sum_{ij}\left[\log P_{ij} - A_i - \frac{B_0'\alpha_i S_j'}{\sigma_i^2}\right]^2$$

$$W_0'' = \sum_{ij}\left[\log P_{ij} - A_i - \frac{B_0''\alpha_i S_j''}{\sigma_i^2}\right]^2$$

$$\hat{W}_0 = \sum_{ij}\left[\log P_{ij} - A_i - \frac{\hat{B}_0'\alpha_i S_j'}{\sigma_i^2} - \frac{\hat{B}_0''\alpha_i S_j''}{\sigma_i^2}\right]^2$$

and this determines B_0', B_0'', $\hat{B}_0'$, $\hat{B}_0''$. A regression to a second order is performed, and the following residual sums of squares are computed.

$$W' = \sum_{i,j}\left[\log P_{ij} - A_i - \frac{B'\alpha_i S_j'}{\sigma_i^2} + \frac{1}{2}\left(\frac{B_0'\alpha_i S_j'}{\sigma_i^2}\right)^2\right]^2$$

$$W'' = \sum_{ij}\left[\log P_{ij} - A_i - \frac{B''\alpha_i S_j''}{\sigma_i^2} + \frac{1}{2}\left(\frac{B_0''\alpha_i S_j''}{\sigma_i^2}\right)^2\right]^2$$

$$\hat{W} = \sum_{ij}\left[\log P_{ij} - A_i - \frac{\hat{B}'\alpha_i S_j'}{\sigma_i^2} + \frac{1}{2}\left(\frac{\hat{B}_0'\alpha_i S_j'}{\sigma_i^2}\right)^2 - \frac{\hat{B}''\alpha_i S_j''}{\sigma_i^2} + \frac{1}{2}\left(\frac{\hat{B}_0''\alpha_i S_j''}{\sigma_i^2}\right)^2\right]^2$$

To test the validity of (i), we set $B_0'' = 0$ and $B'' = 0$. We note that

$$S' = (W' - \hat{W})/1 \quad \text{and} \quad S = \hat{W}/\nu$$

are independent estimates of the same variance provided that hypothesis (i) is true. The ratio

$$F'' = \frac{S'}{S} = \frac{W' - \hat{W}}{\hat{W}}\,\nu$$

is distributed according to the 'F-distribution' with 1 and ν degrees of freedom. The degrees of freedom ν of the residual equals the total sample number minus the number of fitted parameters. Similarly, for hypothesis (ii) the ratio

$$F' = \frac{W'' - \hat{W}}{\hat{W}}\,\nu$$

TABLE 5—*Regression of the pole tide peak near 14 months*

	Station, i					
	1–11	1–4	5–6	7–8	9–10	11
W'	136.88	68.16	39.80	16.37	5.65	5.53
W''	137.91	66.39	41.33	17.92	6.06	5.30
$\hat{W}$	135.72	66.30	39.70	16.16	5.44	6.26
F'	3.87	0.11	1.72	4.57	4.80	0.17
F''	0.28	2.41	1.03	0.53	1.66	1.03
ν	240	86	42	42	42	20
95%	3.92	4.00	4.17	4.17	4.17	4.35
90%	2.75	2.79	2.79	2.84	2.84	2.97

is distributed as $F(1, \nu)$. Values of F' and F'' for various station groups (Table 1) are given in Table 5.

For stations 1 to 4 hypothesis (ii) is favored but not at the 90 per cent level (2.41 does not exceed the 90 per cent upper limit of 2.79). All other groups of stations and the composite average favor (i). A similar analysis (not shown) in the restricted frequency range $j = 60$ to 74 leads to the same conclusions.

References

Bakhuyzen, H. G. Van de Sánde, Über die Änderung der Meereshöhe und ihre Beziehung zur Polhöhenschwankung, *Vierteljahrschr. Astron. Ges., Leipzig, 47,* 218–221, 1913.

Baussan, J., La Composante de Chandler dans la variation des niveaux marins, *Ann. géophys., 7,* 59–62, 1951.

Blackman, R. and Tukey, J., The measurement of power spectra from the point of view of the communications engineer, *Bell System Tech. J., 37,* 185–282, 1958.

Christie, A. S., The latitude variation tide, *Bull. Phil. Soc. Wash., 13,* 103–122, 1900.

Fedorov, E. P., O vliyanii kolebanii urovnya okeana, vizivaemich dvijeniem poliusov zemli, na eto dvijenie, *Doklady Akad. Nauk SSSR, 67,* 647–650, 1949.

Haubrich, R. A., The pole tide, Dissertation for the degree of Doctor of Philosophy (Geology), Univ. of Wisconsin, 1958.

Helmert, F., Neue Formeln für den Verlauf der Schwerkraft im Meeresniveau beim Festlande, *Sitzber. kgl. preuss. Akad. Wiss.,* 676, 1915.

Jeffreys, H., *The Earth,* Cambridge University Press, 1952.

Jeffreys, H., and R. O. Vicente, The theory of nutation and the variation of latitude, *Monthly Notices Roy. Astron. Soc., 117,* 142–161, 1957*a*.

Jeffreys, H., and R. O. Vicente, The theory of nutation and the variation of latitude: The Roche model core, *Monthly Notices Roy. Astron. Soc., 117,* 162–173, 1957*b*.

Kulikov, K. A., The motion of the poles of the earth and variation of latitude, *Ouspekhi Astr. Nauk, 5,* 111, 1950.

Lambert, W., An investigation of the latitude of Ukiah, California, and of the motion of the pole, *U. S. Coast and Geodetic Survey, Spec. Publ. 80,* 62–64, 1922.

Larmor, J., The influence of the oceanic waters on the law of variation of latitudes, *Proc. London Math. Soc.* (2), *14,* 440–449, 1915.

Maksimov, I. V., O "poliusnom prilive" v more i atmosfere zemli, *Trudy Inst. Okeanol. Akad. Nauk SSSR, 8,* 92-118, 1954.

Maksimov, I. V., Poliusnyi priliv v okeane zemli, *Doklady Akad. Nauk SSSR, 108,* 799–801, 1956.

Munk, W. H., and G. MacDonald, *The Rotation of the Earth: A Geophysical Discussion,* Cambridge University Press, 1960.

Munk, W. H., and R. Revelle, On the geophysical interpretation of irregularities in the rotation of the earth, *Monthly Notices Roy. Astron. Soc., Geophys. Suppl., 6,* 331–347, 1952.

Munk, W. H., F. E. Snodgrass, and M. J. Tucker, Spectra of low-frequency ocean waves, *Bull. Scripps Inst. Oceanog.* (in press).

Newcomb, S., On the dynamics of the earth's rotation, with respect to the periodic variations of latitude, *Monthly Notices Roy. Astron. Soc., 52,* 336–341, 1892.

Przybllok, E., Über die sogenannte Polflut in der Ost-und Nordsee, *Veröff. des Preus. Geodasischen Inst., no. 80,* Potsdam, 1919.

Rosenhead, L., Tides on a two-layer earth, *Monthly Notices Roy. Astron. Soc., Geophys. Suppl., 2,* 171–196, 1929.

Takeuchi, H., On the earth tide in the compressible Earth of varying density and elasticity, *J. Fac. Sci., Univ. Tokyo, 7,* 1–153, 1951.

Von Schweydar, W., Die Bewegung der Drehachse der elastischen Erde im Erdkörper und im Raume, *Astron. Nachr., 203,* 103–114, 1916.

Walker, A. M., and A. Young, Further results on the analysis of the variation of latitude, *Monthly Notices Roy. Astron. Soc., 117,* 119–141, 1957.

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Spectral Composition of the Luminescence of the Euphausiid *Thysanoessa raschii*

We have determined the spectral characteristics of the bioluminescence of *Thysanoessa raschii*.

The crustaceans were collected in Loch Fyne, dark-adapted, deep-frozen, and sent to the Plymouth Laboratory, Marine Biological Association, in vacuum flasks.

For the experiments the animals were homogenized in sea water in a small beaker. The homogenate glowed spontaneously with an intensity that did not change appreciably during the experiments.

The instrument used in the laboratory observations is a telemetering bathyphotometer normally used for undersea photometric determinations. The sensor in the instrument is a R.C.A. 931–*A* photomultiplier tube. The signal from this tube is amplified and fed into a Leeds and Northrup 'Speedomax' recorder. The photocathode is just behind a filter holder, in front of which is a collimating tube. At the distal end of the tube is an opal plastic disk with the characteristics of a Lambert collector. The beaker containing the homogenate is placed at the end of the tube. The light is collimated because narrow-band interference filters are used, and their useful angle is limited to 5°. Twelve interference filters were used in the range 420–640 mμ.

The instrument measured irradiance (H), obtained from

$$n \sim kH \sim \mathrm{s}ET_{\mathrm{I}}S\,\mathrm{d}\lambda,$$

where n is recorder reading, E is energy of the source through the wave-length interval $d\lambda$, T_{I} is measured transmission of the individual interference filter through the wave-length interval $\mathrm{d}\lambda$, and S is the relative sensitivity of the photomultiplier tube through the wave-length interval $\mathrm{d}\lambda$. The value of k was obtained from calibration of the entire instrument against a U.S. Bureau of Standards source. Irradiance values were in watts/cm.^{2}, and quanta were derived from Planck's equation. The data were equated to 1·0 at the wave-length of maximum emission.

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All measurements were made in a dark room.

The mean of the luminescent emission from four homogenates of *T. raschii* is shown in Fig. 1. There is a sharp primary peak at about 476 mμ, and a slight secondary inflexion can be detected between 500 and 530 mμ. The spectrum is rather similar to that of *Euphausia pacifica*, the only other euphausiid for which an emission spectrum has been determined. The primary peak of the *E. pacifica* spectrum is at 472 mμ when the results are calculated in quanta, and the secondary inflexion is more pronounced than that of *T. raschii*.

Although the 1957 measurements of *E. pacifica* were made with the same instrument, a different series of interference filters was used, and the terminal glow of animals killed with ammonia was measured.

E. pacifica is an open-ocean form, whereas *T. raschii* is confined to neritic habitats.

We thank Dr. Harold Barnes, Millport, for supplying us with specimens of *T. raschii*, and Dr. F. S. Russell for the hospitality of the Plymouth Laboratory of the Marine Biological Association, where these experiments were undertaken. This work received support from the U.S. National Science Foundation.

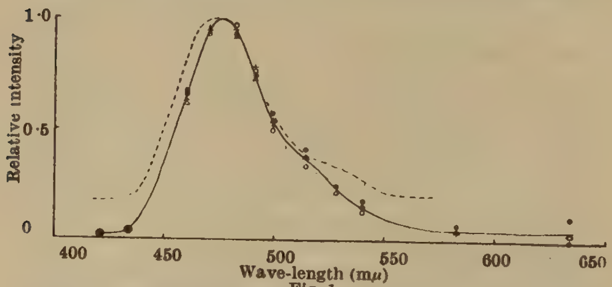

Fig. 1

Fig. 1. Spectral districution of luminescence from *Thysanoessa raschii* (solid line) and *Euphausia pacifica* (broken line). Data on which the curves were based are in quanta equated to 1·0 at the point of maximum emission

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[1] Kampa, E. M., and Boden, B. P., *Deep Sea Res.*, 4 (2), 73 (1957).

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(1092)

Initial Discoveries of Fish Faunas on Seamounts and Offshore Banks in the Eastern Pacific[1]

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THE RECENT DISCOVERY in the Pacific Ocean of numerous submerged mountains (Hess, 1946; Menard and Dietz, 1951; Menard, 1955, and in press), including "banks" (rising to a depth of less than 100 fathoms) as well as the flat-topped "guyots" and other "seamounts" (with minimum depths greater than 100 fathoms), has posed intriguing questions regarding their faunas. Some of these questions are:

What species inhabit the individual banks and seamounts, and in what regularity and abundance?

How did these species become dispersed to and established on these structures?

What bearing may the determined constitution of these isolated faunas have on our ideas concerning past and present oceanic circulation and temperatures?

Do the banks and seamounts (as well as the islands) provide stepping stones for the transgression of narrow to broad oceanic areas, even the supposedly vast eastern Pacific barrier that separates the Indo-Pacific and American faunas (Ekman, 1953: 21, 72, 292)?

May some elements in the faunas of the deeper seamounts be relicts that have become adapted to increasing depths as the seamounts have subsided (or become flooded)? If so, the faunistic evidence may have some bearing on the historical interpretation of the seamounts.

To what degree has isolation on the banks and seamounts led to speciation?

Are either demersal or pelagic fishes (or other animals) sufficiently abundant and available on or over these isolated rises to yield profitable fisheries?

What factors, physico-chemical or biotic, are responsible for the abundance of life on and over these rises? The first thought that comes to mind is that the elevations in the bottom contour induce disturbances in the deep currents, which no doubt have greater velocities than they were long thought to have, and that such disturbances induce upwelling and the enrichment of the upper waters.

Systematic explorations of the faunas on the isolated banks and seamounts (and oceanic islands) should yield rich returns, both scientifically and commercially. As yet only fragmentary information has been accumulated. Some such fragments of data, recently acquired, concerning the fish faunas on seamounts and banks from the Gulf of Alaska to far-off Chile, are presented here.

Embassichthys bathybius (Gilbert) on Pratt Seamount

On August 22, 1951, an adult "deepsea sole" 242 mm. in standard length surprisingly was caught in a rock dredge being hauled at a depth of 510 fathoms on the side slope of Pratt Seamount in the Gulf of Alaska, at Lat. 56° 20′ N., Long. 142° 30′ W., about 210 nautical miles offshore. It was obtained by Henry W. Menard and John D. Isaacs on the research ship "Horizon," on the Northern Holiday Expedition of the Scripps Institution of Oceanography (Dredge No. 5; Collection SIO 53-187).

This record constitutes a notable northward as well as seaward extension of the range of this deep-water pleuronectid. Long known

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only from off southern California, recently it has been reported from off northern California (Hagerman, 1950) and from off Washington (Welander and Alverson, 1954: 42–43).

Unpublished records show that this commercially utilizable fish is not uncommon in deep waters off northern California and Washington. It is becoming of minor importance in the trawl fishery, as operations are being extended into deeper water. Its occurrence on at least one seamount suggests the possibility that the trawling grounds may eventually be extended far seaward, where depths are appropriate.

I have underway a distributional and variational study of this poorly-known flounder.

Sebastodes ruberrimus Cramer and Other Fishes on Cobb Seamount

A rockfish caught on Cobb Seamount, about 280 nautical miles off Washington and about 240 miles southwest of Vancouver Island, at Lat. 46° 44′ N., Long. 130° 47′ W., was described by Welander and Alverson (1954: 37–40, figs. 1, 2) as representing a new species, *Sebastodes bilineatus*. By examining this specimen (No. 10099, University of Washington Fish Collection) in detail on June 11, 1956, I verified the belief of Julius B. Phillips, W. I. Follett, and myself that it is a specimen of the large *S. ruberrimus*, in the striped, juvenile stage. The contrast between the dark ground color and the light stripes is unusually bold, but since color intensity varies so greatly in fishes and since all other characters observed fall within the observed range of variation of *S. ruberrimus*, it seems doubtful that the species is modified on Cobb Seamount. Slight differentiation, however, is a remote possibility. Data on the type of *S. bilineatus* will be included in a forthcoming contribution by Hubbs and Follett.

Thompson (1915: 121) observed that *S. ruberrimus* is "the most abundant of all species of the genus on the halibut banks," but in the same paper described what is now thought to be a specimen of this species as *S. babcocki*, new species.

Welander and Alverson mentioned that the type of *S. bilineatus* was one of 30 fish specimens "caught by personnel of the U. W. oceanography vessel Brown Bear in the vicinity of Cobb Seamount on August 7, 1953." It is to be hoped that complete lists of species taken on or about each seamount will be published.

Perhaps fisheries may develop on the seamounts for rockfishes (*Sebastodes* spp.), as well as for the halibut, *Hippoglossus stenolepis* Schmidt, and other flatfishes.

SHORE AND PELAGIC FISHES ON BANKS AND SEAMOUNTS OFF CENTRAL CALIFORNIA

A number of coastal and pelagic fishes of expectable species were recorded by Follett (1952) from several banks and seamounts off the central California coast, at no very great distance offshore. This is not to mean, however, that high interest and potential importance is not to be attached to such inshore rises.

TUNAS AND TUNA FORAGE FISHES FROM "STRANGER BANK" ("HURRICANE BANK")

In 1957, on an expedition from Scripps Institution of Oceanography, on the research ship "Stranger," Adrian F. Richards discovered, at Lat. 16° 52′ N., Long. 117° 30′ W., roughly 200 nautical miles southwest of Clarion Island, a shallow bank rising from oceanic depths to a depth of approximately 15 fathoms. This bank was assigned the tentative name Stranger Bank by the discoverer. Tuna fishermen of San Diego, who dub the structure "Hurricane Bank," from the heavy weather often encountered there, promptly began fishing there and in less than a year had taken from the newly found fishing ground well over 1,000 tons of yellowfin tuna, *Neothunnus macropterus* (Temminck and Schlegel), and smaller quantities of skipjack tuna, *Katsuwonus pelamis* (Linnaeus). At the time of writ-

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ing it is evident that within the first full year the catch will definitely exceed 2,000 tons, with a value to the fishermen of more than one-half million dollars; and the relative proximity of the ground represents a great saving in expenses. Tuna fishermen have reported taking some rainbow runners, *Elegatis bipinnulatus* (Quoy and Gaimard), from this same bank.

During the Island Current Survey of May–June, 1958, personnel of the Inter-American Tropical Tuna Commission caught about the bank a number of young yellowfin tuna. On June 1 an adult male of the labrid *Bodianus diplotaenius* (Gill) was caught on the shoalest part of the bank (it was identified from a kodachrome). Many sharks, including some hammerheads, *Sphyrna* sp., were seen, to confirm the reports that sharks abound here. On June 5 one wahoo, *Acanthocybium solandri* Cuvier, was caught, and several mantas, presumably *Manta hamiltoni* (Newman), were seen.

Further information on other fishes that live over and about this bank comes from an initial examination of stomach contents of yellowfin tuna, collected there for the Inter-American Tropical Tuna Commission and now being analyzed by the staff of the Commission. Young to half-grown specimens of the spiny trunkfish, *Lactoria diaphana* (Bloch and Schneider), constitute a notably high proportion of the food. Some stomachs are filled with this bony creature, which elsewhere has been found to be eaten by this tuna. This trunkfish ranges very widely through tropical regions, and even, on occasions, as far northward as California. A sample (SIO 58–56) from the stomach of a tuna caught on this bank comprises 487 specimens of this trunkfish, 13 to 44 mm. in standard length. Another lot (SIO 58-57) comprises 7 specimens, of similar size. One tuna contained a large young triggerfish (SIO 58-54) of the common, wide-ranging, more or less pelagic species *Xanthichthys lineopunctatus* (Hollard); its standard length is 52 mm. Remains of flying fish of undetermined species also occur in the tuna stomachs.

A thorough study of the fish fauna of Stranger Bank is much to be desired, especially in view of the thorough analysis of the Revillagigedo fish fauna being conducted by Boyd W. Walker and associates.

For information and material on the fishes and fisheries of this bank I am indebted to Bell M. Shimada and Franklin G. Alverson of the Inter-American Tropical Tuna Commission and to Wilbert M. Chapman of the American Tunaboat Association.

Pterygotrigla picta (Günther) on a Guyot far off Chile

On January 26, 1958, a triglid fish (gurnard or sea robin) of considerable zoogeographical interest was captured incidentally in a rock dredge being hauled at a depth of 129 fathoms on a guyot rising from an extensive ridge in the southeastern Pacific. It was preserved by Robert H. Parker on the research ship "Spencer F. Baird" of Scripps Institution of Oceanography, on the I. G. Y. Downwind Expedition (Station 73; SIO 58-42). This unnamed guyot is at Lat. 25° 44′ S., Long. 85° 25′ W., which is about 800 miles off the Chilean coast, about 300 miles westerly from Isla San Felix, and nearly 600 miles northwest of Isla Juan Fernández. It is in a region where seamounts appear to be numerous, and is on a submarine ridge that seems to extend westward at least to Easter Island (Fisher, 1958: 20–25, figs. 1, 8, 9).

Although the specimen is young (54 mm. in standard length) and was badly crushed posteriorly in the rock dredge, it seems identifiable as *Pterygotrigla picta* (Günther). This species was originally very briefly described, but magnificently figured, by Günther (1880: 24–25, pl. 13, fig. A), as *Trigla picta*, on the basis of a 10.5-inch specimen collected by the "Challenger" on Isla Juan Fernández, far off the coast of Chile. The species has been reported also from New Zealand and Australia (McCulloch, 1929: 393), but not from the

American mainland. This distributional pattern seems to be related to the bottom topography within the south temperate zone of the Pacific: there is a very deep trench off the Chilean coast, but from the vicinity of islas Juan Fernández and San Felix westward numerous submarine ridges and peaks rise to various heights below and above sea level. It may be predicted that the species will be found not only on the guyot nearly 600 miles northwest of Juan Fernández, but also on other rises between the offshore islands of Chile and New Zealand. It is not known whether seamounts intervene between Juan Fernández and San Felix, and it is now doubted that the long charted intervening ridge exists.

This young specimen differs in a number of respects from the characters indicated in the original description and figure of *Trigla picta*, but these differences seem attributable to age and individual variation. The dorsal spines number VIII instead of VII, but the eighth is short and very slender (and is perhaps concealed in the type); the number of dorsal soft rays (12) agrees. The anal rays are 11, not 12, but some variation is expected. (The principal caudal rays number 6 + 5 = 11, and each pectoral has 15 rays, in the formula i, 9, ii + 3.) The nuchal spine is much longer, reaching to below the base of the third dorsal spine (probably as a function of youth), and is about as long as the humeral spine. (The pectoral fin, as in the type, reaches to about the seventh anal ray.) The preopercular spine (at the end of the cheek ridges) is double, rather than single, but the lower point is definitely the smaller, and it probably becomes obsolete in larger fish. The body is similarly marked with light-ringed blackish spots, but these spots (as expected) are fewer. On the head the spots are discernible, though faint, as though just developing. The fins, unlike those on the type, are unspotted: in the spinous dorsal the membranes are sooty outward; the second dorsal has a submarginal dark band; the pectoral is very dark, except for a light border; the other fins are almost wholly clear. In coloration the young specimen corresponds better with the figure given by Mann (1954: 309) for the "pez mariposa de Juan Fernández," which he designated *Chelidonichthys pictus*.

Trigla picta has been referred, properly I think, to the genus *Pterygotrigla* Waite (1899: 108), which was based on the Australian species *Trigla polyommata* Richardson. Although quite different in coloration, *P. picta* and *P. polyommata* seem very similar in structure.

The genus *Pterygotrigla* has been attributed to Japan (Matsubara and Hiyama, 1932: 8–14, figs. 2–5), but the Japanese species referred to the genus differ trenchantly from *P. picta* and *P. polyommata* in lacking vomerine teeth. They are also said to have a "distinct anal spine" (a hardened soft-ray?), which does not seem to be true of the Southern Hemisphere species. Though the two groups agree in many characters it seems advisable to put them in separate genera. The name *Otohime* Jordan and Starks (1907) is available for the common Japanese species *hemisticta* (the type species), and probably for *Pterygotrigla ryukyuensis* Matsubara and Hiyama.

Otohime differs further from *Pterygotrigla* in the small size of the dorsal bucklers. The distinction in the first anal ray may not be valid, for a young specimen of *Otohime hemisticta* has this ray paired, articulated, and flexible.

It seems clear from the original account that *Trigla guttata*, which was described without comparisons by Philippi (1896: 375–376) from Juan Fernández, is a synonym of *Pterygotrigla picta* (Günther)—as was assumed by McCulloch (1929: 393). But the gurnard from Islas Juan Fernández that was figured and discussed by Mann (1954: 309) as *Trigla punctata* Philippi obviously belongs in a very different species. From the figure it seems clearly referable to *Chelidonichthys*, as defined by Matsubara and Hiyama (1932: 4). It even seems probable that the specimen may be referred to *C. kumu* (Lesson and Garnot), an important species that is accorded a range from New Zealand and Australia to Japan (see Matsubara and Hiyama, 1932: 5–7, fig. 1). Like *Pterygotrigla*, *Chelidonichthys* is unknown in Chile. Its occurrence on Juan Fernández parallels that of *Pterygotrigla picta*, and it may be predicted that *Chelidonichthys* will be found on seamounts, banks, or islands between Juan Fernández and New Zealand.

Both *Pterygotrigla* and *Chelidonichthys* belong to a distributional category that may be classified as antitropical Indo-Pacific, and contrast sharply with the American triglids (*Prionotus* and the derived *Bellator*). Comparison of a specimen of *P. picta* from Isla Juan Fernández (an adult 340 mm. in standard length collected by the Mellon Expedition in Bahia Cumberland on February 28, 1936) with specimens of *Chelidonichthys kumu* from Japan discloses many differences. The row of keeled scales along the entire dorsal base is replaced by greatly enlarged flat bucklers along the base of the spinous dorsal only. *P. picta* differs further from *C. kumu* in a feature of the lateral line, which ends simply, immediately beyond the caudal base, instead of being forked and continued as two or three lines across the caudal fin. The head is much larger, and the body is much more contracted at the base of the caudal fin, which is sharply forked rather than merely emarginate. The orbital rim is spineless, but the opercular, nuchal, and humeral spines are greatly enlarged. The nape, in advance of the greatly enlarged buckler surrounding the first dorsal spine, is scaleless rather than scaly. The teeth are almost shagreenlike; those of the lower jaw are deflected outward over the anterior edge of the lower lip. The vomerine teeth are in an oval rather than a broadly V-shaped patch. Most of these differences show in the figures reproduced by McCulloch (1922: 119, pl. 39).

NEED FOR FURTHER STUDIES

These brief notes tend to show that great scientific as well as commercial importance may be attached to a study of the faunas of the many banks and seamounts that rise toward the surface from the depths of the Pacific Ocean. Many and perhaps most of these structures seem capped and surrounded by productive water. The spectacular take of tuna on the Stranger, or Hurricane, Bank has been mentioned. Milner B. Schaefer, director of research for the Inter-American Tropical Tuna Commission, has assured me that good catches have been made about other banks and even about seamounts that nowhere closely approach the surface. Henry W. Menard of the Institute of Marine Resources, University of California, leading student of seamounts, tells me that he has obtained strong field indications, from echograms, that large objects (presumably fish or giant squid) form a halo around and far above many seamounts between California and Hawaii. It seems highly probable, as is stated in the introduction, that the submarine mountains, even those that are isolated and deep, disturb the currents sufficiently to induce extensive upwelling.

The benthic faunas of the banks and seamounts do not give promise of such commercial potential, but may prove of greater scientific interest, particularly in respect to zoogeography and speciation.

REFERENCES

EKMAN, SVEN. 1953. *Zoogeography of the Sea.* xiv + 417 pp., 121 figs. Sidgwick and Jackson, Ltd., London.

FISHER, R. L. (Editor). 1958. Preliminary report on Expedition Downwind, University of California, Scripps Institution of Oceanography IGY Cruise to the southeast Pacific. IGY World Data Center A, National Academy of Sciences, IGY General Report Series Number 2: i–iii, 1–58, figs. 1–21.

FOLLETT, W. I. 1952. Annotated list of fishes collected by the California Academy of Sciences during six cruises of the U. S. S.

"Mulberry" conducted by the United States Navy off central California in 1949 and 1950. *Proc. Calif. Acad. Sci.* 27: 399–432, pls. 21–26.

GÜNTHER, ALBERT. 1880. Report on the shore fishes procured during the voyage of H. M. S. "Challenger" in the years 1873–1876. IN *The Voyage of H. M. S. "Challenger,"* Zoology 1(6): 1–82, pls. 1–32.

HAGERMAN, FREDERICK B. 1950. The extension of the range of the deep sea flounder, *Embassichthys bathybius* (Gilbert). *Calif. Fish Game* 36: 165–166, fig. 52.

HESS, H. H. 1946. Drowned ancient islands of the Pacific Basin. *Amer. J. Sci.* 244: 772–791, figs. 1–8B.

JORDAN, DAVID STARR, and EDWIN CHAPIN STARKS. 1907. Note on *Otohime*, a new genus of gurnards. *Proc. U. S. Nat. Mus.* 32: 131–133, 1 fig.

MANN F., GUILLERMO. 1954. *La vida de los peces en aquas chilenas.* Ministerio de Agricultura [and] Universidad de Chile, Santiago de Chile. 342 pp., many figs.

MATSUBARA (formerly Sakamoto), KIYOMATSU, and YOSIO HIYAMA. 1932. A review of the Triglidae, a family of mail-cheeked fishes, found in the waters around Japan. *J. Fish. Inst. Tokyo* 28: 3–67, figs. 1–22.

McCULLOCH, ALLAN R. 1922. Check list of the fish and fishlike animals of New South Wales. Part iii. *Aust. Zool.* 2, pt. 3: 86-130, pls. 25–43.

McCULLOCH, ALLAN R. 1929. A check-list of the fishes recorded from Australia. *Mem. Aust. Mus.* 5, pt. 3: 329–436.

MENARD, HENRY W. 1955. Deformation of the northeastern Pacific basin and the West Coast of North America. *Bull. Geol. Soc. Amer.* 66: 1149–1198, figs. 1–30, pl. 1.

——— In press. Submarine vulcanism in the Pacific Basin. *Proc. 20th Int. Geol. Cong.*

MENARD, HENRY W., and ROBERT S. DIETZ. 1951. Submarine geology of the Gulf of Alaska. *Bull. Geol. Soc. Amer.* 62: 1263–1285, figs. 1–10, pls. 1–5.

PHILIPPI, R. A. 1896. Peces nuevos de Chile. *An. Univ. Chile* 93: 375–390.

THOMPSON, WILLIAM F. 1915. A new fish of the genus *Sebastodes* from British Columbia, with notes on others. *Rep. B. C. Comm. Fish.* 1914: 120–122, 1 pl.

WAITE, EDGAR R. 1899. Scientific results of the trawling expedition of H. M. C. S. "Thetis." Fishes. *Mem. Aust. Mus.* 4: 25–128, figs. 3–10, pls. 1–30.

WELANDER, ARTHUR D., and DAYTON L. ALVERSON. 1954. New and little known fishes of the eastern Pacific. *Fish. Res. Pap. Wash. Dept. Fish.* 1(2): 37–44, figs. 1–2.

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THERMOCLINE TOPOGRAPHY, HORIZONTAL CURRENTS AND "RIDGING" IN THE EASTERN TROPICAL PACIFIC

TOPOGRAFIA DE LA TERMOCLINA, CORRIENTES HORIZONTALES Y "ONDULACION" EN EL PACIFICO ORIENTAL TROPICAL

by — por
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La Jolla, California
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THERMOCLINE TOPOGRAPHY, HORIZONTAL CURRENTS AND "RIDGING" IN THE EASTERN TROPICAL PACIFIC[1]

by

Townsend Cromwell

INTRODUCTION

A primary objective of the Inter-American Tropical Tuna Commission is a knowledge of the ecology of tunas which inhabit the Eastern Tropical Pacific. This paper presents some results of the work in physical oceanography, which, it is hoped, will be useful to the biological work and at the same time of interest to physical oceanographers. The work presented here was begun in connection with simple observable facts; the thermocline is very close to the sea surface in a region off Costa Rica (Wooster and Cromwell, 1958), and this region is biologically productive (Holmes, *et al.*, 1957; Brandhorst, 1958). It is the main object of this study to describe and explain these facts, insofar as possible.

THERMOCLINE TOPOGRAPHY

The first step in the study was the construction of seasonal charts to show thermocline depth over the entire Eastern Tropical Pacific, and in particular to describe the interesting area off Costa Rica. The charts were constructed in collaboration with W. Brandhorst, who has used a fall chart in connection with his study of the distribution of zooplankton standing crop (Brandhorst, 1957). The data used were all of the bathythermograph cards from the Eastern Tropical Pacific (about 4000) on file in the BT Section at the Scripps Institution of Oceanography of the University of California. Thermocline depth, i.e., depth to the bottom of the surface layer, was read from each card. Anyone who has worked with bathythermograph cards will know of the very real difficulties in making an objective definition to fit this concept of thermocline depth. In perhaps three-quarters of the cards, there was no ambiguity, but in the remaining, more complicated cases, each was compared to those nearby and a somewhat subjective decision had to be made.

Monthly averages of thermocline depth were obtained for each one-degree square. If more than one observation was made in a square during a single 24-hour period, these were averaged first, the result then being used in computing the average for the month. Finally, averages for each quarter (Jan.-Mar., etc.) were determined from the monthly averages.

[1] Contribution from Scripps Institution of Oceanography. NEW SERIES, No. 1137

The quarterly averages were plotted and contoured and the resulting seasonal charts appear as Figure 1. Ridges and troughs in the thermocline are indicated by R and T. The number of days on which one or more observations were made in each one-degree square appear as insets to the figure. It is apparent that the data are sparse.

Each chart was contoured independently of the other three, but then it was necessary to make minor changes in order to increase the regularity of identity and progression, season to season, of the major troughs and ridges. While contouring, a concerted effort was made not to be influenced by preconceived notions about the horizontal currents, i.e., the contours were drawn on the basis of the observations of thermocline depth alone.

The general impression given by the charts is one of a series of troughs and ridges, oriented roughly east-west. For the purposes of this discussion, attention is drawn to the shallow thermocline off Costa Rica near 9°N, 90°W, persistent the year round. Except in spring, it seems to be separated from the coast. During summer and fall it lies at the east end of a long ridge, whereas in winter and spring it is nearly an isolated dome. This area will be referred to as the Costa Rican Thermal Dome, or, for convenience, simply the "dome." There are several additional areas where the thermocline is close to the sea surface (<10 m), notably the ridge along the equator. Immediately south of the dome (winter) there is an intense hollow. During summer and fall, this area is part of a long trough oriented east-west.

HORIZONTAL CURRENTS

The topography of the thermocline as presented in the charts gives information about the geostrophic current. This interpretation is most reliable where the ocean approximates a two-layer system, as it does, reasonably well, in the tropics south of the transition, near 18°N. (Wooster and Cromwell, 1958). North of this transition, the ocean departs radically from a two-layer system. Only the persistent features and intense gradients of the thermocline topography will be interpreted as indicating horizontal current. Because these charts, so interpreted, revealed unexpected features of the circulation, it was decided to go to the current observations published by the U. S. Navy Hydrographic Office (Anonymous, 1947) for an independent check. The data of this publication are averages by one-degree squares, of all "current set" observations filed at the Hydrographic Office, presented in monthly charts. In each square, there is an arrow pointing direction of set and two numbers, one representing the average magnitude of set in miles per day and the other, the number of observations going into the average. The number of observations for each month ranges from as many as several hundred in some squares near the coast to only a few or none in many off-shore areas.

Figure 2 presents data from the Hydrographic Office charts for February and August, plotted as vectors. The data are somewhat erratic where sparse, but it was felt that an objective comparison with the thermocline topography demands that no data be smoothed or eliminated. The charts are each internally consistent without smoothing, and the major flows are apparent.

Where the current is strong, agreement between it and thermocline topography is good, i.e., the flow is approximately along the contours, the thermocline sloping upward to the left of an observer facing downstream in the Northern Hemisphere. Two major features of the horizontal circulation will be emphasized here, that associated with the Costa Rican Thermal Dome, and the behavior of the Equatorial Countercurrent.

It has been suggested that the dome is associated with the north edge of the Equatorial Countercurrent and a northward coastal current (Wooster and Cromwell, 1958), i.e., with cyclonic shear. Cyclonic shear appears in this area on each of the seasonal streamline charts presented by Fleming (1940). This idea is supported here by Figures 1 and 2.

Referring to the chart of thermocline topography for winter, the geostrophic model predicts a Countercurrent of limited east-west extent between the dome and the hollow located immediately to the south. A current of this type is apparent in the February current chart extending from 92° to 83°W. with its axis lying along 7½°N. Further examination of the current chart reveals that the Countercurrent forms part of a closed anticyclonic circulation around the hollow. This eddy is semi-permanent, unlike those found along the edge of the Gulf Stream (Fuglister, 1951) which, because they exist irregularly in space and time, are not found on average charts. It may be nearly fixed geographically. But, on the other hand, this is a monthly average current chart, and the eddy may have only a statistical existence, like the semi-permanent circulation cells of the atmosphere. The cyclonic circulation associated with the dome is also semi-permanent, but this latter circulation does not close in the west.

The short segment of east current is all that remains of the Equatorial Countercurrent in the Eastern Tropical Pacific during winter according to the data of the Hydrographic Office chart. The February chart shows a Countercurrent farther to the west. Thus, the Countercurrent is discontinuous, or at least it is not present in all longitudes at the surface, during February. This is true also during other winter-spring months according to the Hydrographic Office charts. During summer, as shown by the arrangement of ridges and troughs on the chart of thermocline topography (Figure 1-c) and by the surface current chart for August, the Countercurrent is continuous in the Eastern Tropical Pacific.

THE COSTA RICAN THERMAL DOME

A complete physical explanation for the Costa Rican Thermal Dome is not apparent. Comparison of the charts of thermocline topography based on BT observations with those of horizontal current based on observations of "current set," establish that the shallow thermocline off Costa Rica coincides with cyclonic shear. Thus, the current is quasi-geostrophic. One might expect the dome to be closest to the sea surface during the season that cyclonic shear is maximal, but it does not seem possible to determine from the Hydrographic Office charts which season this is.

There is some reason to believe that the depth of the thermocline generally over the Eastern Tropical Pacific and, hence, of the dome, is related to a large scale phenomenon, namely, to the strength of the trade winds. The sea surface in the tropics is known to slope upwards toward west and there is an associated opposite slope to the thermocline. Maintenance of these longitudinal slopes of the sea surface and the thermocline are attributed to the west-directed stress of the trade winds. It follows that when the Northern Hemisphere (northeast) trades are strongest, the thermocline in the Eastern Tropical Pacific should be shoalest.

Charts of sea surface temperature show a low center in the area of the dome in northern winter (Anonymous, 1944). Since the wind in this area is light and variable the year round, implying no more vertical mixing in winter than in summer, the low temperature at this time may indicate that the thermocline is shoalest and that it "outcrops" most frequently during northern winter. At this time, farther to the west, the Northern Hemisphere (northeast) trades are strongest (Crowe, 1950).

Thus, it may be that the dome is closets to the sea surface when, 1) the stress of the trades over the ocean to the west is greatest and when 2) the cyclonic current shear across the dome is greatest. Why the thermocline is at any *particular* depth, however, is not explained.

VERTICAL MOTION

It seems to this author that progress toward an understanding of certain physical processes in the ocean is being hindered by an indiscriminate use of the word "upwelling." Vertical motions of several distinctly different types are commonly lumped in this category. An analogous situation would exist if we were to use the word "advection" for all horizontal water movements, without bothering to distinguish among tidal currents, inertial currents, geostrophic currents, etc. The dynamics are different for each of these current types and each has been measured in rather pure form, substantiating its existence in the ocean. In general, though, the horizontal flow at any particular place and time is a composite of several types and the analogous difficulty enters when one attempts to study the vertical components. Useful distinctions among certain phenomena involving vertical motion can be made now, but these concepts are generally more vague than those concerning horizontal motion and a really good classification of vertical motion probably awaits a better understanding of the phenomena involved.

The data indicate that vertical motion of differing types occurs in the tropical Pacific. There are now available a number of meridional sections across the equatorial currents of the central Pacific (Montgomery, 1954; Austin, 1954; Stroup, 1954). The author has published two sets of drawings showing the fields of density (as approximated by σ_t), salinity inorganic phosphate and dissolved oxygen (Cromwell, 1953, and the sections of σ_t and inorganic phosphate are repeated here as Figure 3. Differences between upwelling and what might be called "ridging," are apparent in these drawings. The sections of Figure 3, as do the others cited above, show that the *surface layer* at the equator is relatively dense and phosphate-rich. This dense, nutrient-rich surface water at the equator is so distant (horizontally) from a possible source that it is concluded that it came from below. Since, in addition, theory predicts strong divergence of the wind drift current along the equator it is further concluded that the process which brings this water into the surface layer from below, is upwelling (Cromwell, 1953).

This sequence of observational results and interpretation is that which has been presented as evidence of upwelling in the coastal waters of Peru (Gunther, 1936), South Africa (Defant, 1936) and California (Sverdrup and Fleming, 1941). Thus, there is a precedent for what oceanographers might accept as the meaning of the term "upwelling." In a sentence, upwelling is the upward motion brought about by divergence of the wind drift current. It is envisaged here as a complex process characterized primarily by a continuing upward transport of water from the upper thermocline, into the surface layer.

Actually, the theory of upwelling has advanced well beyond the simplified version stated above (Yoshida, *et al.*, 1953; Hidaka, 1955a, and b), but divergence of surface water moved by the wind and a continuing replacement from below seem still to be a basic ingredient of the upwelling process in each of these theories.

Ridging: The situation at the north boundary of the Equatorial Countercurrent is entirely different. The boundary between east and west-flowing water lies between 10° and 11°N in Figure 3. Here the surface layer is not phosphate rich and its density is low. These facts are apparent in many published sections. It is known that the thermocline rises and falls at this boundary, but the water motion here must be of a different nature than that occuring in regions of upwelling.

One might speculate concerning the nature of motion in a vertical plane oriented transversely to accelerating, quasi-geostrophic currents. Part a of Figure 4 depicts the mass distribution in the absence of current. Parts b and c represent the motion that may occur in this plane during the (transitory) development of quasi-geostrophic currents. As illustrated in b, for example, a dense ridge, oriented perpendicularly to the page, will develop as quasi-geostrophic currents accelerate in the sense indicated (⊗ away from and ⊙ toward reader, Northern Hemisphere). Divergence in the surface layer and convergence below the thermocline (each involving ageostrophic motion) could account for "ridging" of the thermocline. Motion of the thermocline itself will be vertical. If the ageostrophic components were in the opposite sense, "troughing" would occur. If the divergence and convergence were spread throughout thick layers, slight ageostrophic components could result in what would be considered profound changes in thermocline depth in a short time.

This has been almost, but not quite, pure speculation. The one compelling fact, which is the excuse for presenting the idea at all, is that the data suggest strongly that water motion during ridging occurs with negligible transfer from the thermocline, into the surface layer. The circulation proposed here could accomplish this.

Dietrich (1935) has described a region off the southeast coast of Africa in which there is a shallow thermocline associated with a quasi-geostrophic current. The phenomenon is the same as that at the north boundary of the Equatorial Countercurrent and Dietrich called the process by which such shallow thermoclines are formed, "dynamic upwelling." To make the separation of phenomena complete, the word "upwelling" might be retained for the more active, continuing upward movement, produced by a divergent wind drift current.

The words "ridge" (the feature) and "ridging" (the process) are used here. These words are descriptive and are defined, in the sense intended, as are the counterparts, "trough" and "troughing."[1] When the major axis of a ridge or trough is short, the words "dome" and "hollow" can be used.

Transfer of water upward from the thermocline: The shallow thermocline, persistent the year round off Costa Rica, has already been described. The area is separated from land by a relatively thick surface layer. It is located in the heart of the doldrums (see, for example, Crowe, 1951). For

[1] Each of these words is defined in the Unabridged, Second Edition of Webster's New International Dictionary.

these reasons it is considered to be an example of ridging, (or doming), not upwelling. At times the dome may intersect the sea surface, i.e., it may "outcrop." It is so indicated in Figure 5 by the way in which the thermocline is drawn, but there is some question as to whether or not there is a surface layer in BT F67-2. These BT data were obtained from the Scripps Institution research vessel BAIRD during the period Nov. 30-Dec. 2, 1955, on Eastropic Expedition.

Obviously, during outcropping, properties associated with the thermocline will be exposed at the sea surface. If no process other than ridging were effective, then the surface layer, when the thermocline is submerged, should be of low-density, nutrient-poor water. This is not the case. Measurements have shown that the surface layer in the immediate vicinity of the dome is, at least sometimes, relatively phosphate rich (Wooster and Cromwell, Profile XVe, 1958). Thus, when the thermocline is exceptionally close to the sea surface, some process or processes lead to nutrient enrichment of the thin surface layer. This fact needs an explanation, without recourse to upwelling. It has been suggested that vertical mixing may be the important mechanism (Wooster and Cromwell, 1958).

Vertical stirring and mixing induced at the ocean surface: It is intended here that "vertical stirring and mixing" refer to the small scale, turbulent phenomenon, with eddies of dimensions approximating the thermocline depth, a process produced by the action of the wind or by cooling from the sea surface with resultant overturning. The effect of this process in enriching the surface layer at the dome will be discussed only qualitatively.

It seems reasonable that vertical stirring and mixing can cause water in the thermocline to enter the surface layer more easily the closer the thermocline is to the surface. Orbital velocities associated with sea surface waves decrease exponentially with depth and the effectiveness of mixing might, therefore, be expected to decrease similarly. Putting it another way, the effectiveness of mixing upward from the thermocline may increase exponentially with decrease in surface layer thickness. As mentioned previously, the dome is found in the doldrums with wind force Beaufort 2-3 predominating. Even these light winds, however, together with overturn due to surface cooling at night, must produce some vertical mixing.

It might be added that the increase in concentration resulting from the addition of a certain amount of substance to the surface layer (by vertical mixing or by any other means) varies with the geometry of the surface layer. Assume, for example, that the surface layer generally contains .30 μg at. L^{-1} of inorganic phosphorus. One meter of thermocline water containing 1.00 μg at. L^{-1} of inorganic phosphorus is mixed throughout the surface layer which was originally 5 meters thick in one place and

10 meters in another. The concentrations in the resulting 6 and 11 meter layers will be .42 μg at. L^{-1} and .36 μg at. L^{-1}, respectively. Thus, if vertical mixing were uniformly effective everywhere in the ocean in the sense that the rate at which the nutrient substances are added to the surface layer from below were constant, relatively high concentrations of nutrient salts might be expected to occur over shoal thermoclines.

Results of tank experiments: Tank experiments conducted by Rouse and Dodu (1955) reveal an interesting feature of the vertical stirring and mixing process. Their equipment consisted of a vertical, round, cylinder into which they placed fresh water over salty water, forming a two-layered system separated by a sharp interface. The upper layer was then agitated by a mesh which was driven regularly up and down by a motor. They noted that irregular waves formed on the interface and that some of these waves became unstable in the upper layer, but not in the lower layer. Thus, the denser fluid mixed into the surface layer, but not vice versa. The surface layer tended to thicken, at the expense of the lower, and a stationary interface was maintained in the experiment by introducing salty water at the bottom of the tank and withdrawing the mixture from near the surface. It might be mentioned that similar experiments by the present author in which the interface was allowed to descend revealed that it did so at roughly an exponential of the time. If one is willing to apply the results of these tank experiments to the ocean (a speculative procedure) it is possible to set up a circulation hypothesis.

Hypothesis of ageostrophic motion at the dome: The experiments suggest that vertical stirring and mixing have the effect of increasing surface layer thickness (or thermocline depth) and that the rate of surface layer thickening is exponentially related to thermocline depth. Thus, turbulence induced at the sea surface will tend to increase thermocline depth at the dome center at a rate that is very large compared to the rates in the surrounding region. The thermocline can remain stationary only in the presence of an upward velocity component which must be of greatest magnitude at the dome center. Continuity of mass then demands that there be divergent flow in the surface layer and convergence in the thermocline (Figure 6). Heat energy balance must then be maintained by heat flow in a sense opposite to the arrows representing mass transport, i.e., by mixing. The temperature gradient is seen to be properly dircted for this. This proposal has been largely a kinematic one. The source of energy for the circulation is not known, but it does not seem to involve a divergent wind drift current.

A final comment might be made on the effect of "radiation surplus" by which is meant the net transfer of heat energy across the sea surface through radiation, evaporation, and sensible transfer. The rate of surplus at the dome is, on an annual average, 100 gm cal cm^{-2} day^{-1} (Sverdrup, 1942, p. 230), added to the sea. In this case, it is not necessary to maintain heat energy balance in the surface layer at the dome entirely by horizontal mixing, as part of the loss by vertical mixing can be made by the radiation surplus. In fact, it would be possible for the layer at the dome to be a center of enrichment by vertical mixing and, at the same time, a warm center. This could not be true in an area of heat energy loss from the sea.

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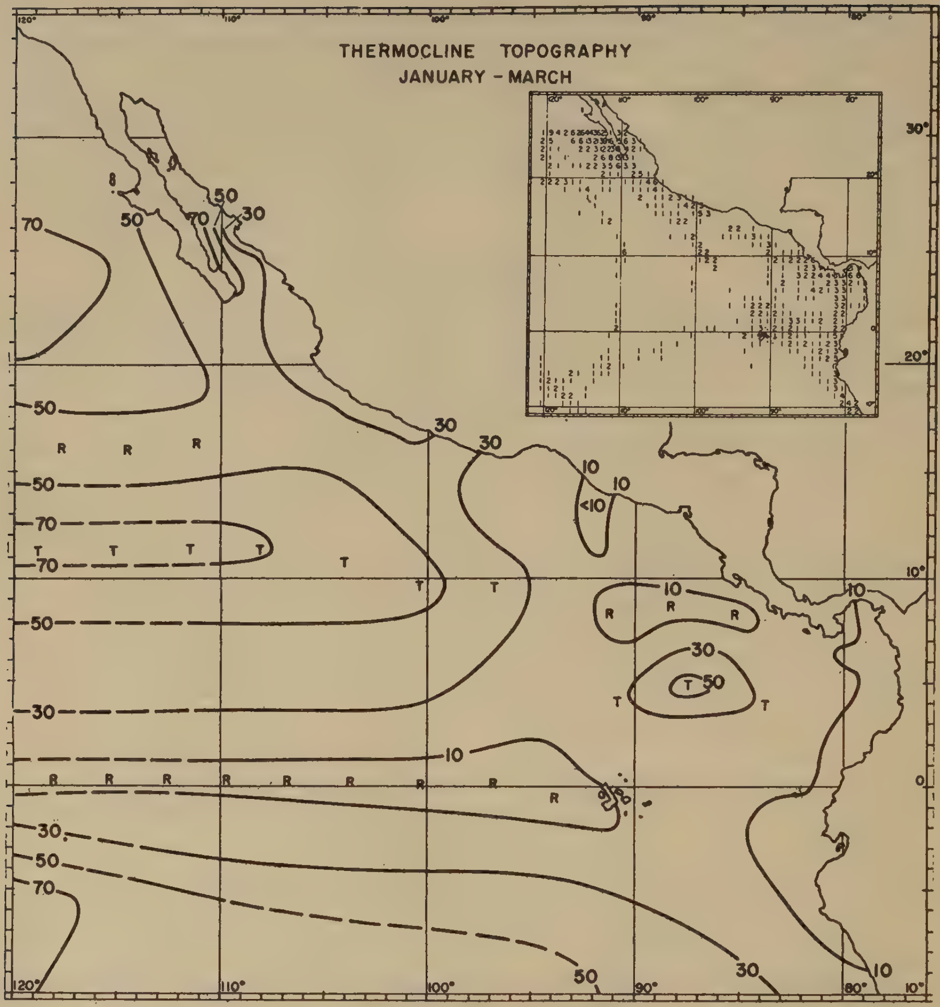
THERMOCLINE TOPOGRAPHY
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120°
110°
100°
90°
80°
30°
20°
10°
0
10°
70
50
30
10
<10
R
T

Figure 1-a Depth to the top of the thermocline. Standard contour interval, 20 meters. Dashed contour indicates uncertain extrapolation through region with no data. Ridge and trough lines indicated by R and T. Inset: Number of days on which at least one observation obtained in particular degree squares.

Figura 1-a Profundidad hasta la cima de la termoclina. Intervalo standard de contorno, 20 metros. Contorno de línea interrumpida indica extrapolación incierta a través de la región sin datos. Líneas de convexidad y concavidad indicadas por R y T. Figura intercalada: número de días en que se obtuvo por lo menos una observación en ciertas áreas rectangulares.

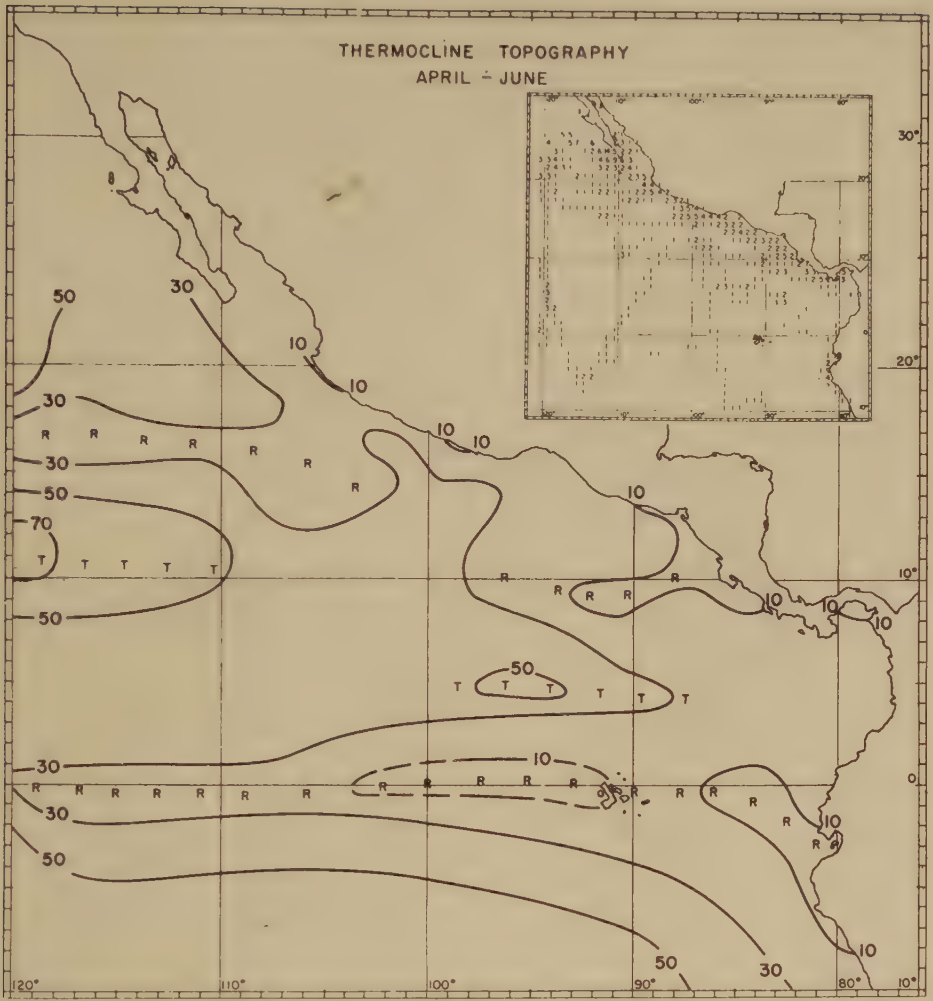

THERMOCLINE TOPOGRAPHY
APRIL - JUNE
50
30
10
10
30
R
30
50
70
T
50
10
50
30
30
50
10
50
30
10
120°
110°
100°
90°
80°
30°
20°
10°
0
10°

Figure 1-b Legend as for Figure 1-a.

Figura 1-b Misma leyenda que la de la Figura 1-a.

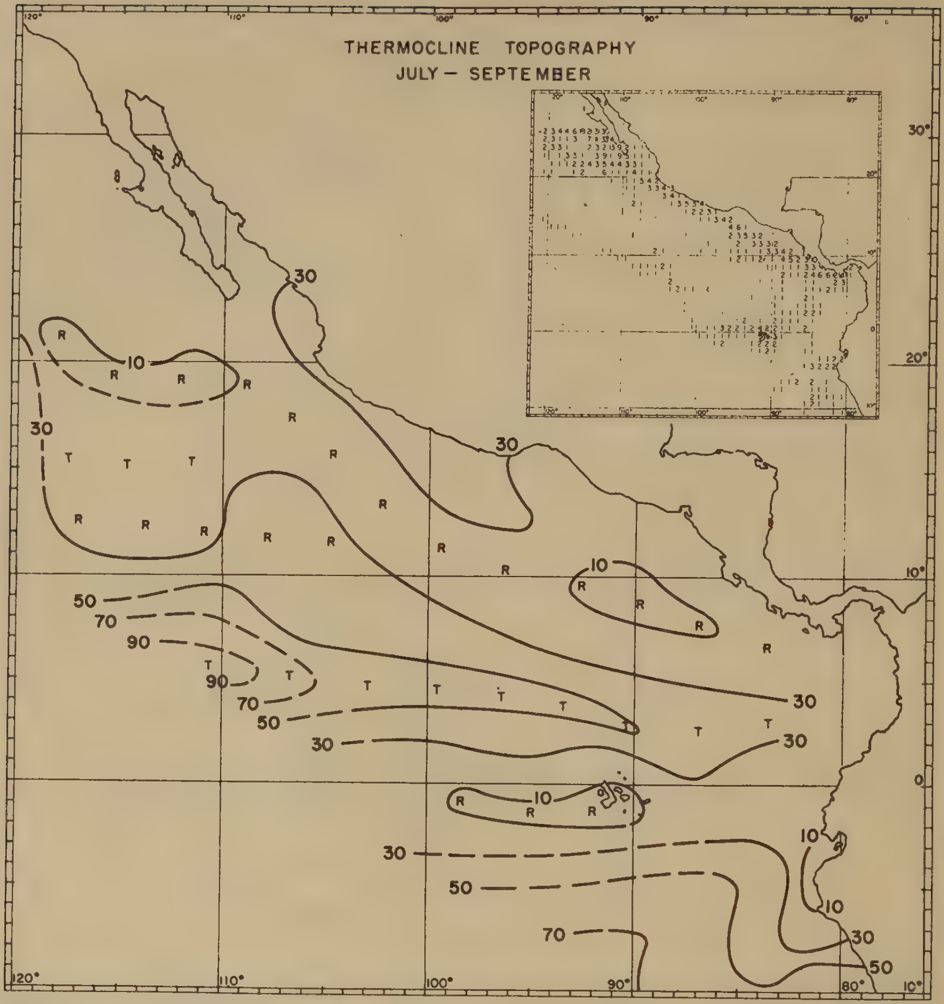

THERMOCLINE TOPOGRAPHY
JULY — SEPTEMBER
120°
110°
100°
90°
80°
30°
20°
10°
0
10°
10
30
50
70
90
R
T

Figure 1-c Legend as for Figure 1-a.

Figura 1-c Misma leyenda que la de la Figura 1-a.

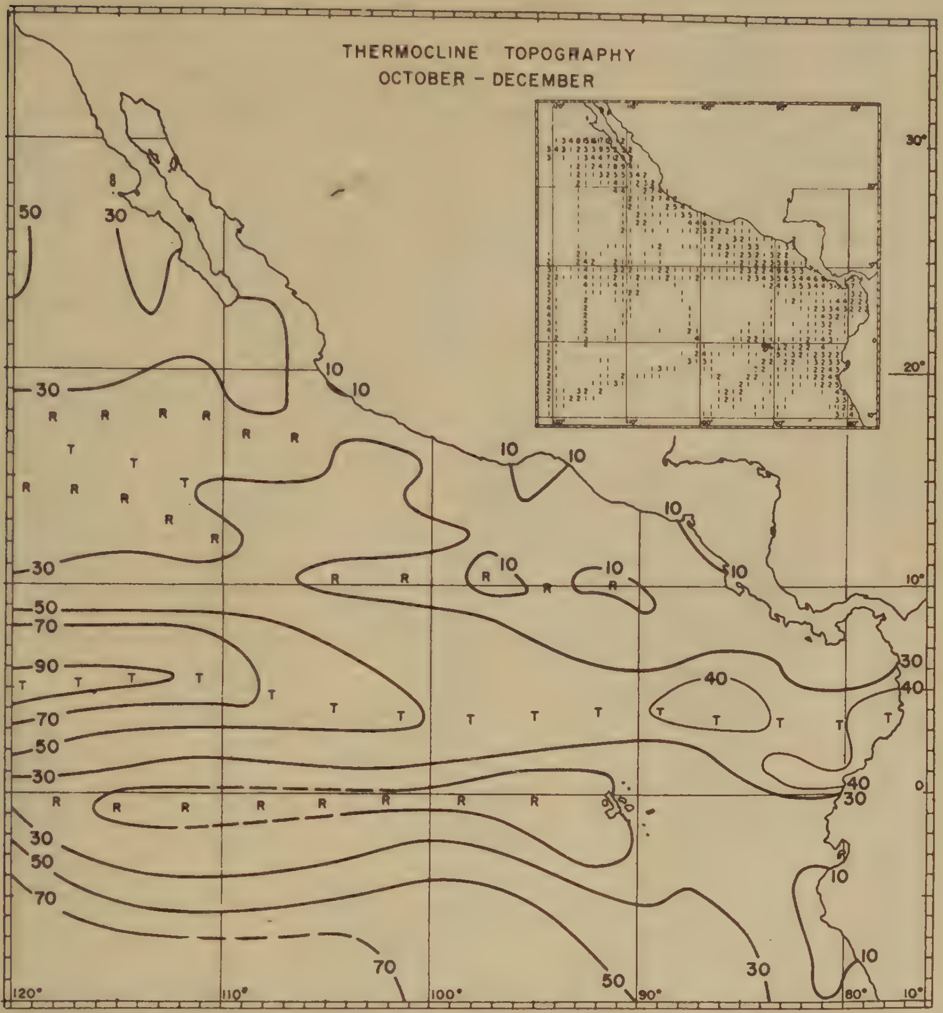

THERMOCLINE TOPOGRAPHY
OCTOBER - DECEMBER
50
30
10
30
R
T
30
50
70
90
70
50
30
40
30
50
70
70
50
30
10
40
30
30°
20°
10°
0
10°
120°
110°
100°
90°
80°

Figure 1-d Legend as for Figure 1-a.

Figura 1-d Misma leyenda que la de la Figura 1-a.

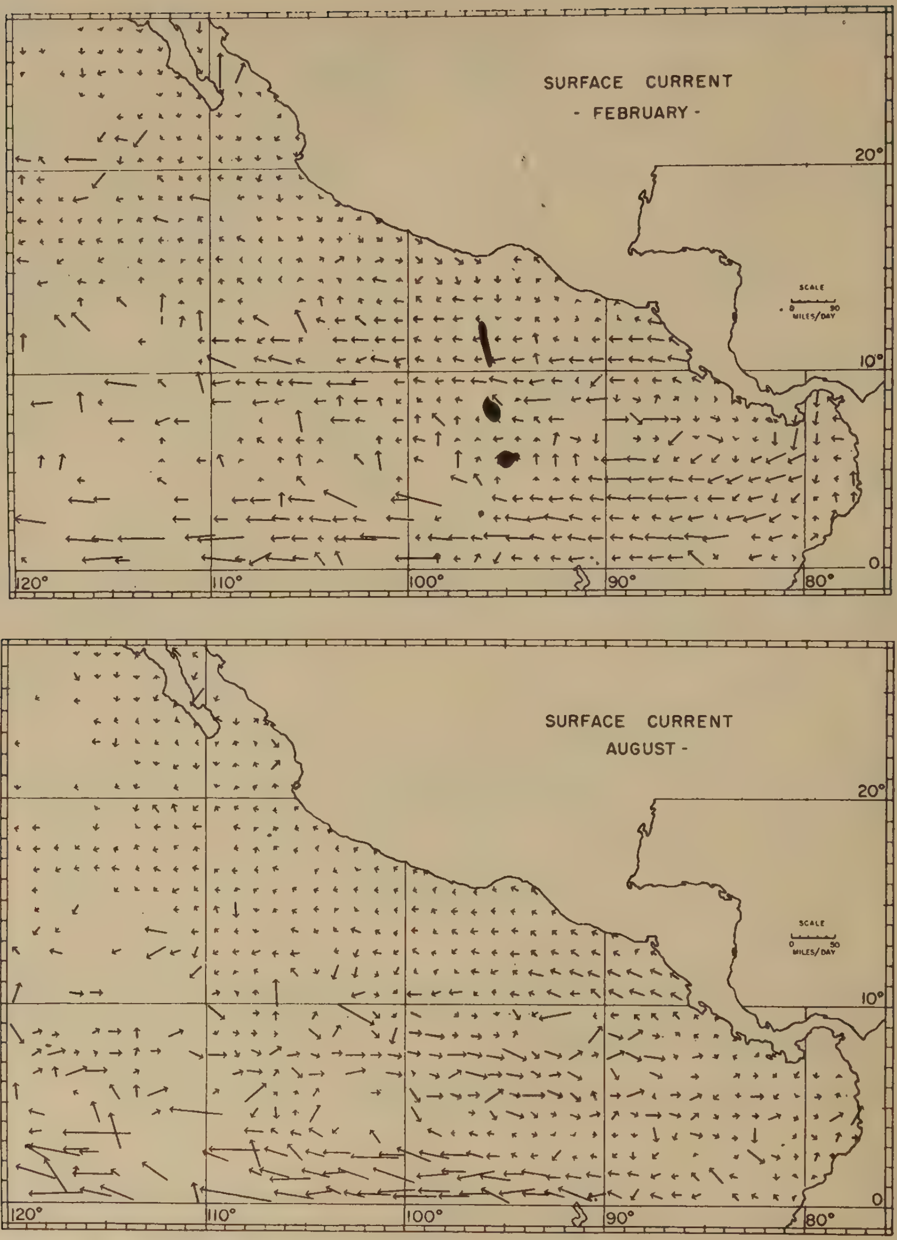
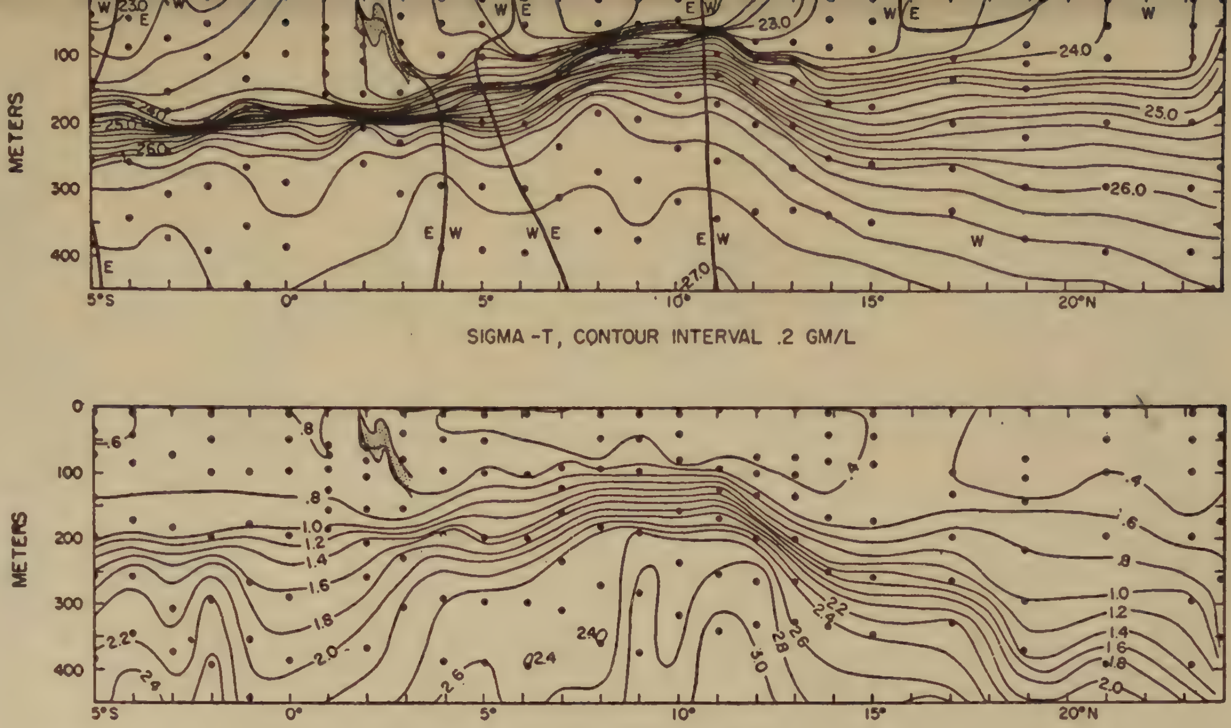

SURFACE CURRENT
- FEBRUARY -
SCALE
0 50
MILES/DAY
20°
10°
0
120°
110°
100°
90°
80°
SURFACE CURRENT
AUGUST -
SCALE
0 50
MILES/DAY
20°
10°
0
120°
110°
100°
90°
80°

Figure 2. Average surface current vectors for February and August.

Figura 2. Vectores de la corriente superficial promedio para febrero y agosto.



SIGMA -T, CONTOUR INTERVAL .2 GM/L

PHOSPHATE - P, CONTOUR INTERVAL .2 μG AT/L

Figure 3. Cross sections of σ_t and inorganic phosphate along 172°W., based on observations by M/V Hugh M. Smith, Jan. 26-Feb. 8, 1950. Shaded zone in surface layer is a front. Boundaries between east-flowing (E) and west-flowing (W) currents drawn on σ_t section, outside 3° parallels. Dense, phosphate-rich surface layer near equator indicates upwelling. Surface layer over ridge at Countercurrent boundary (10-11°N) is of low density and phosphate-poor.

Figura 3. Corte transversal de σ_t y fosfato inorgánico a lo largo del 127° O., basado en observaciones del buque M/V HUGH M. SMITH, en el período enero 26-febrero 9 de 1950. La zona sombreada en la capa superficial es un frente. Los límites entre las corrientes que se desplazan hacia el este (E) y oeste (W) están dibujados en la sección σ_t, fuera del paralelo de 3°. La capa superficial densa, rica en fosfato cerca del ecuador indica "afloramiento". La capa superficial sobre la convexidad en el límite de la Contracorriente (10-11°N) es de densidad baja y pobre en fosfato.

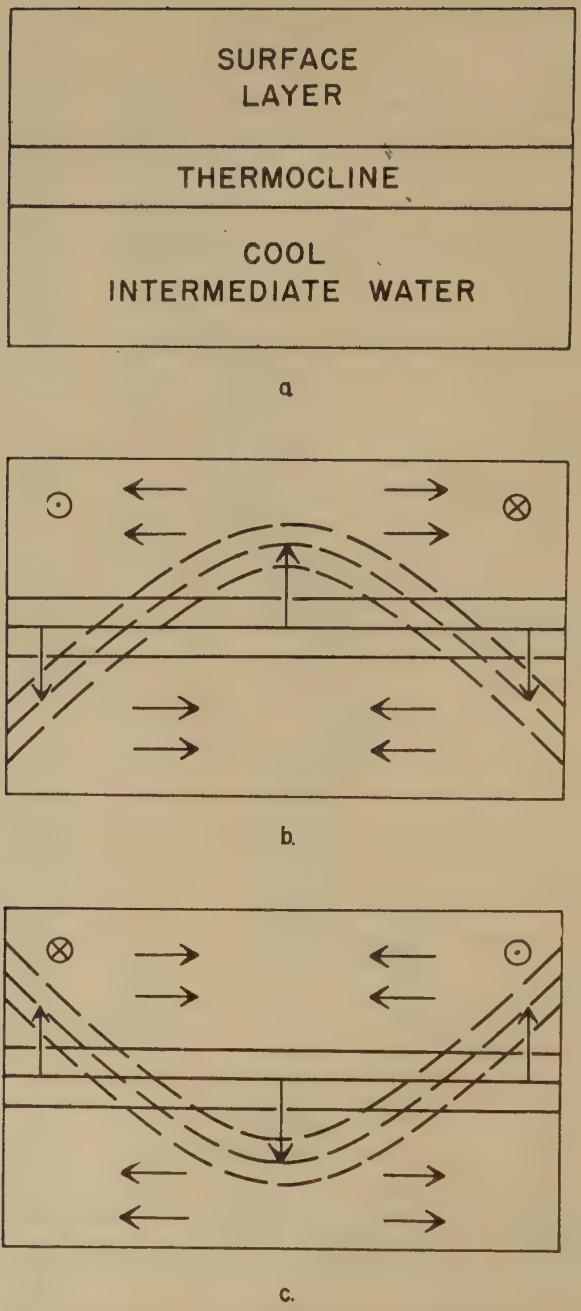

SURFACE LAYER
THERMOCLINE
COOL INTERMEDIATE WATER
a
b.
c.

Figure 4. Motion transverse to accelerating quasi-geostrophic currents (ageostrophic components), a speculation.

Figura 4. Movimiento transversal a las corrientes aceleradoras casi geostróficas (componentes ageostróficos), una especulación.

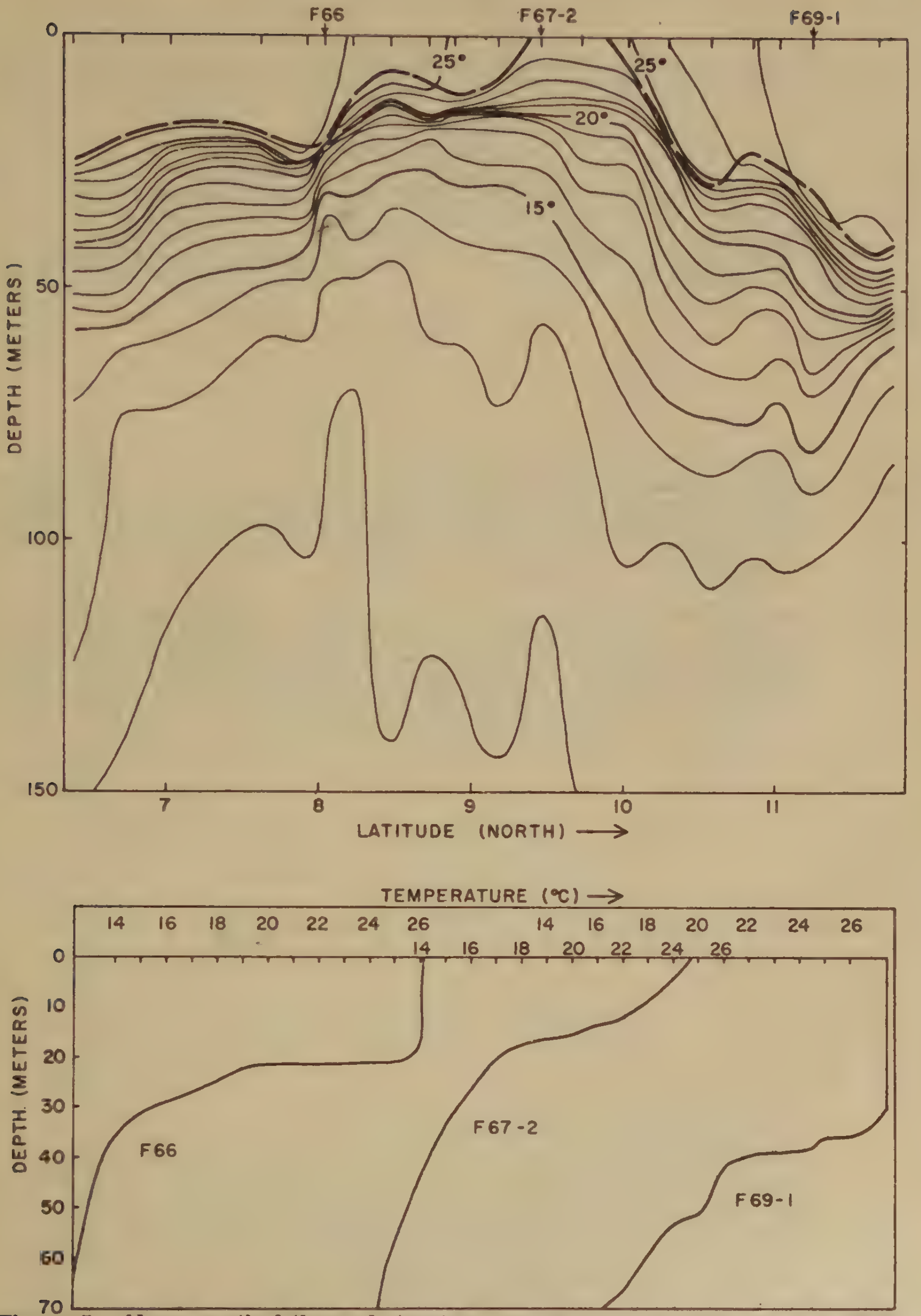


Figure 5. Above, vertical thermal structure through dome at approximately 89°W, based on BT's. Heavy, broken line indicates top of thermocline. Ticks along top mark positions of BT observations. Vertical temperature gradients at positions marked by arrows, appear in lower panel.

Figura 5. Arriba, estructura térmica vertical a través del domo en aproximadamente 89° O., basada en registros BT. La línea gruesa interrumpida, indica la cima de la termoclina. Los gradientes de temperatura verticales en las posiciones marcadas por flechas, aparecen en la parte inferior.

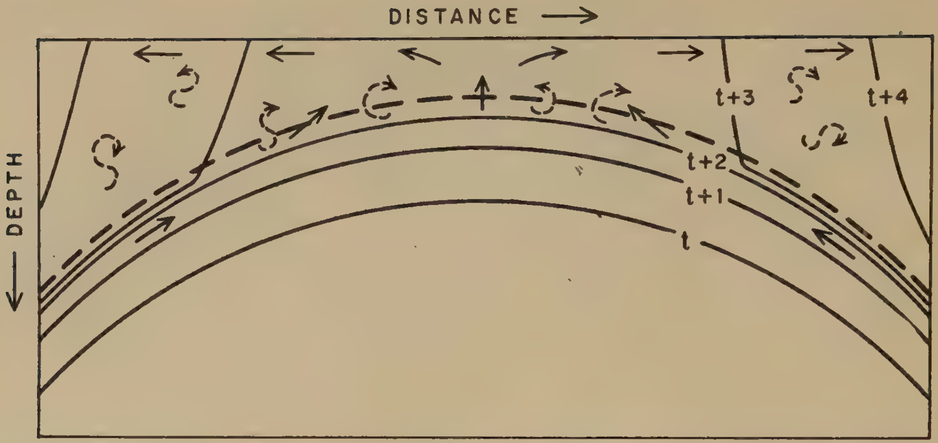


Figure 6. Surface induced vertical turbulence (dashed arrows) penetrates thermocline most effectively where it is shoal, resulting in pronounced surface layer enrichment at the dome. In order that thermocline (dashed curve) and isotherms (solid curves) remain stationary, a circulation (solid arrows) must exist. Qualitative, schematic.

Figura 6. Turbulencia vertical inducida por la superficie (flechas interrumpidas) penetra en la termoclina más efectivamente donde está cerca de la superficie, resultando un enriquecimiento pronunciado de la capa superficial en el domo. Para que la termoclina (curva interrumpida) y las isotermas (curvas sólidas) queden estacionarias, debe existir una circulación (flechas sólidas). Representación cualitativa, esquemática.

ADRIAN F. RICHARDS
U. S. Navy Hydrographic Office, Washington, D. C.

Geology of the Islas Revillagigedo, Mexico

1. Birth and development of Volcán Bárcena, Isla San Benedicto (1)

(With 5 text-figures and 28 plates)

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Abstract

On August 1, 1952, a new volcano named Bárcena was born on Isla San Benedicto, which is located about 300 nautical miles off the west coast of Mexico. A pyroclastic cone nearly 1100 feet above sea level was formed by August 2. By mid-September cone formation had ceased and a small lava plug capped the magma conduit in the crater. After a period of quiescence from mid-September until early November activity resumed and blocky, soda trachyte lava formed two domes in Bárcena crater during November and early December. On December 8 lava flowed through the base of the volcano and formed a delta nearly one-half mile out to sea by the end of February, 1953. All activity, except solfataric steaming, stopped by this date.

Volcanic density flows (« *nuées ardentes* ») descended the cone during the period of cone formation. As the expulsion of ash and steam decreased in early September, 1952, the

exterior of the cone is believed to have been furrowed by these avalanches. Volcán Bárcena has an index of explosiveness of about 90 per cent, the highest of any known oceanic volcano in the eastern Pacific Ocean. Calculations indicate that about 10,500 million cubic feet (300 million cubic meters) of tephra and lava were erupted during the life of Bárcena.

Introduction

General statement and location.

There are few volcanoes whose birth and development have been witnessed by man. In the western hemisphere the life of the only new volcano studied in detail, prior to the birth of Volcán Bárcena, was Parícutin (Foshag and González R., 1956). Unlike Parícutin, which was under almost continuous surveillance, Bárcena was visited only occasionally for periods of a few hours to a few days during its brief period of activity. Yet, apparently without exception and despite the remote location, observers fortuitously were present at all crucial periods of the volcano's development including its birth. The eruption of Bárcena is especially significant because it is the first recorded historic pumice eruption in the eastern Pacific Ocean basin (Williams, 1952).

Volcán Bárcena is located on the southern part of Isla San Benedicto, which is the third largest and most northeastern of the four Islas Revillagigedo of Mexico (Fig. 1). The island is located about 220 nautical miles south of Cabo San Lucas, Baja California, and nearly 300 miles west of Cabo Corrientes on the Mexican mainland.

This paper is the first of a proposed series of papers which will deal with the terrestrial and submarine geology of the individual Islas Revillagigedo and adjacent area.

Previous investigations and literature.

The initial study of Bárcena through October, 1952, was made by Dr. Robert S. Dietz, who conducted the first scientific investigation of the new volcano on two flights to Isla

San Benedicto in September, 1952 (Dietz, 1953). Prof. Howel Williams, who was on the second flight, prepared a geological sketch map of San Benedicto during the time the plane circled the island and later wrote a brief statement on the early activity (Williams, 1952).

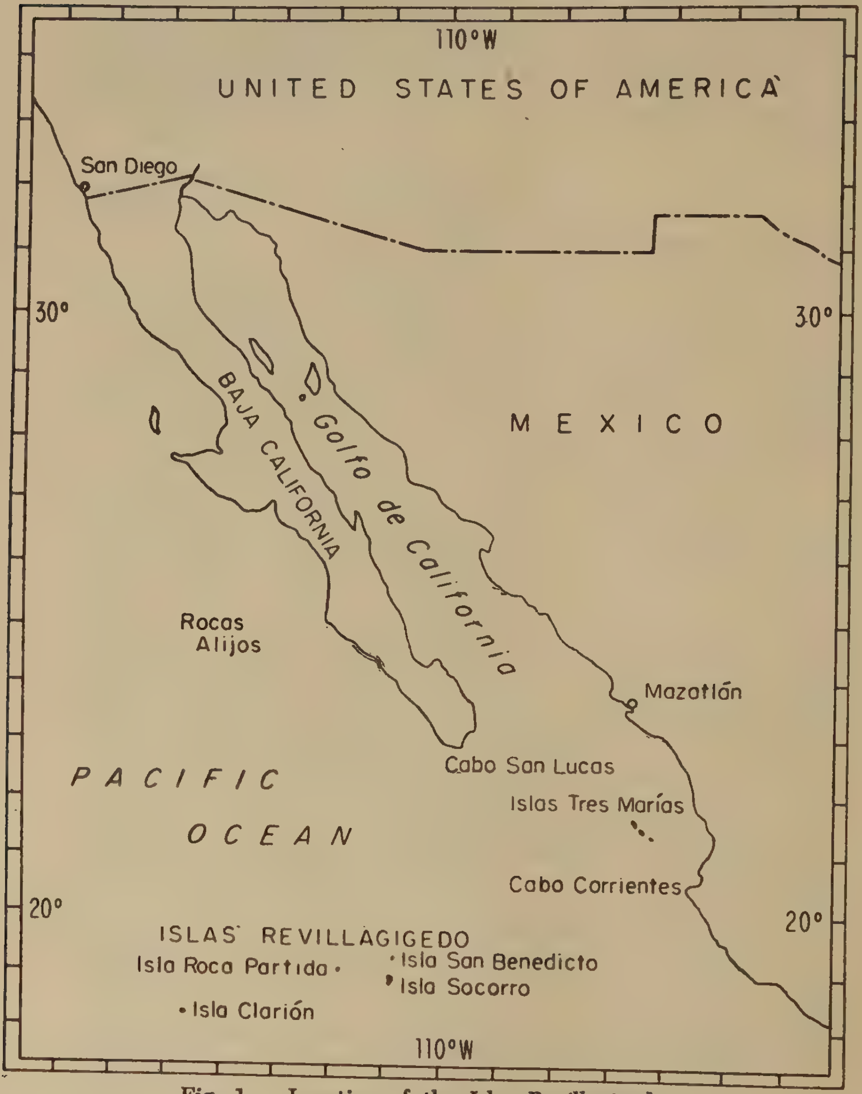
110°W
UNITED STATES OF AMERICA
San Diego
30°
30°
BAJA CALIFORNIA
Golfo de California
MEXICO
Rocas Alijos
Mazatlán
Cabo San Lucas
Islas Tres Marías
PACIFIC OCEAN
Cabo Corrientes
20°
20°
ISLAS REVILLAGIGEDO
Isla Roca Partida
Isla San Benedicto
Isla Socorro
Isla Clarión
110°W

Fig. 1. - Location of the Islas Revillagigedo.

A preliminary account of the development of Bárcena was prepared in 1953 by RICHARDS and DIETZ (1956). Additional brief reports on particular phases of the early activity of the volcano were written by DIETZ and RICHARDS (1953), RICHARDS (1953), and RICHARDS and WALKER (1954). The present paper represents part of the writer's Ph. D. dissertation, « Geology, volcanology, and bathymetry of Isla San Benedicto, Mexico », submitted to the University of California, Los Angeles, in 1957.

An investigation of sounds made by the erupting volcano was made by SNODGRASS and RICHARDS (1956) from November, 1952, to May, 1955. RICHARDS (1958) reported on a trans-Pacific drift of floating San Benedicto pumice which originated from the eruption and was collected on Hawaii, Johnston, Wake, and the Marshall Islands. The pumice is believed to have reached the Palau Islands, which are located in the western Pacific Ocean.

Fieldwork.

Five visits by sea were made to Isla San Benedicto from 1952 to 1957 (Table 1). On these visits a total of ten days were spent on land and five days at sea. Ten U. S. Navy photographic and observation flights to San Benedicto were planned by the writer with the help of the photographic officers of Photographic Squadron Sixty-one, Utility Squadron Seven, and Patrol Squadron Forty-six from November, 1952, to January, 1956. He participated on seven of them.

The majority of observations of Volcán Bárcena during the period of cone building and lava extrusion were made by men of the California tuna fishing fleet.

Names of geographic features.

Prior to the birth of Bárcena the only names of geographic features in general use were the following: Ash Heap (Montículo Cinerítico), Herrera Crater, White Bluffs, and Black Bluff. The latter two names are no longer applicable

Table 1.

Observations of Volcán Bárcena: 1952 - 1957.

Date	Observer (1)	Ship or airplane
1952		
August 1	J. da Luz R. Petrie F. Rodriques	Tuna clipper M/V *Challenger*
August 12	C. Blasko T. Howell	Tuna clipper M/V *Intrepid* and its seaplane
September 12	G. Anderson R. S. Dietz R. H. Finch	U. S. Air Force B29, 55th Strategic Reconnaissance Squadron
September 20	E. Boldrick R. S. Dietz H. Williams	U. S. Air Force B29, 55th Strategic Reconnaissance Squadron
November 12-15	M. Neves, Jr.	Tuna clipper M/V *Constitution*
November 15	D. L. Inman A. F. Richards J. M. Snodgrass	U. S. Navy PBM, Squadron VU-7
November 16-17	R. Madruga	Tuna clipper M/V *American Ladies*
November 19	J. Madruga G. Zeluff	Tuna clipper M/V *Paramount*
December 4, 7-9	E. Perriera M. A. Silva	Tuna clipper M/V *Star of the Sea*
December 7-9	J. da Luz	Tuna clipper M/V *Challenger*
December 8	C. Marino	Tuna clipper M/V *Santa Margarita*
December 9	G. Zeluff	Tuna clipper M/V *Paramount*
December 9-12	N. C. Bunker, in charge	Yacht *Observer*
December 11	A. F. Richards V. Silva	Seaplane of the M/V *Southern Queen*
December 13	J. Zolezzi	Tuna clipper M/V *St. Mary*
December 13	J. Canepa	Tuna clipper M/V *Shasta*
1953		
January 4-5, 12	J. Baker P. Lynn	Tuna clipper M/V *Cape Beverly*
February 27	E. Mitchell R. H. Morton	Tuna clipper M/V *Columbus*

(1) Where more than three persons participated on a trip only the person in charge is listed.

(1124)

Table 1 (continued)

Date	Observer	Ship or airplane
March 9-13, 28	B. H. Brattstrom H. Dana A. F. Richards	R/V *Paolina T*, Scripps Institution of Oceanography
circa March 23	V. Silva	Seaplane of the M/V *Southern Queen*
April 16	W. Bascom A. F. Richards J. M. Snodgrass	U. S. Navy P4Y-1P, Squadron VJ-61
May 20	R. MacAllister A. F. Richards J. M. Snodgrass	U. S. Navy P4Y-1P, Squadron VJ-61
July 13	A. F. Richards J. M. Snodgrass	U. S. Navy P4Y-1P, Squadron VJ-61
September 21	S. D. Hinton A. F. Richards J. M. Snodgrass	U. S. Navy P4Y-1P, Squadron VJ-61
November 17-20	A. F. Richards, in charge	R/V *Crest*, Scripps Institution of Oceanography
1954		
August 6	(photographic flight only)	U. S. Navy AJ-2P, Squadron VJ-61
October 28	B. H. Brattstrom H. L. Mason A. F. Richards	U. S. Navy P4Y-1P, Squadron VJ-61
1955		
March 25	J. H. Cawley A. F. Richards	U. S. Navy P5M, Squadron VP-46
May 1-5	A. F. Richards, in charge	R/V *Crest*, Scripps Institution of Oceanography
May 27	(photographic flight only)	U. S. Navy AJ-2P, Squadron VJ-61
1956		
January 26	(photographic flight only)	U. S. Navy AJ-2P, Squadron VJ-61
1957		
March 18	A. F. Richards, in charge	R/V *Stranger*, Scripps Institution of Oceanography

because the features were obliterated during or shortly after the eruption.

In September, 1952, Prof. Howel WILLIAMS suggested the name Boquerón, meaning Big Mouth, for the new volcano (DIETZ, 1953, p. 26). Boquerón Crater was formally proposed in a letter written in October, 1952, by Dr. DIETZ to the Mexican Ambassador in Washington, D. C. In July, 1953, an answer was received that the Department of Agriculture of the Mexican Government and the Geological Institute of the National University had proposed the name of the distinguished Mexican geologist Mariano BÁRCENA for the new volcano following a suggestion of the late Ing. Teodoro FLORES, Director of the Instituto de Geología (Carl FRIES, Jr., personal communication). Volcán Bárcena is preferable to Boquerón and has been adopted; a volcano named Boquerón is located in the Mexican State of Chiapas (SAPPER, 1937, p. 11).

The new names used in Figure 2 were proposed by the writer and translated from English into Spanish by Dr. FRIES. Their etymology is described by RICHARDS and BRATTSTROM (1959).

Acknowledgments.

I acknowledge my gratitude to the numerous people who have assisted me in the field, donated photographs, and discussed various aspects of this study. Unfortunately space does not permit individual recognition. I particularly wish to thank all of the cooperative and friendly tuna fishermen whose contribution to the understanding of this volcano cannot be over emphasized.

Mr. Lewis WAYNE WALKER, my companion on the December, 1952, visit, earned by admiration for his photographic ability and cheerfulness in the field. He personally supplied considerable quantities of film so that a complete record of Bárcena's activity could be obtained.

The trip from California to Isla San Benedicto in December, 1952, was made possible by Mr. Woodrow KRIEGER,

co-owner of the yacht *Observer*, and Dr. Bruce HALSTEAD,

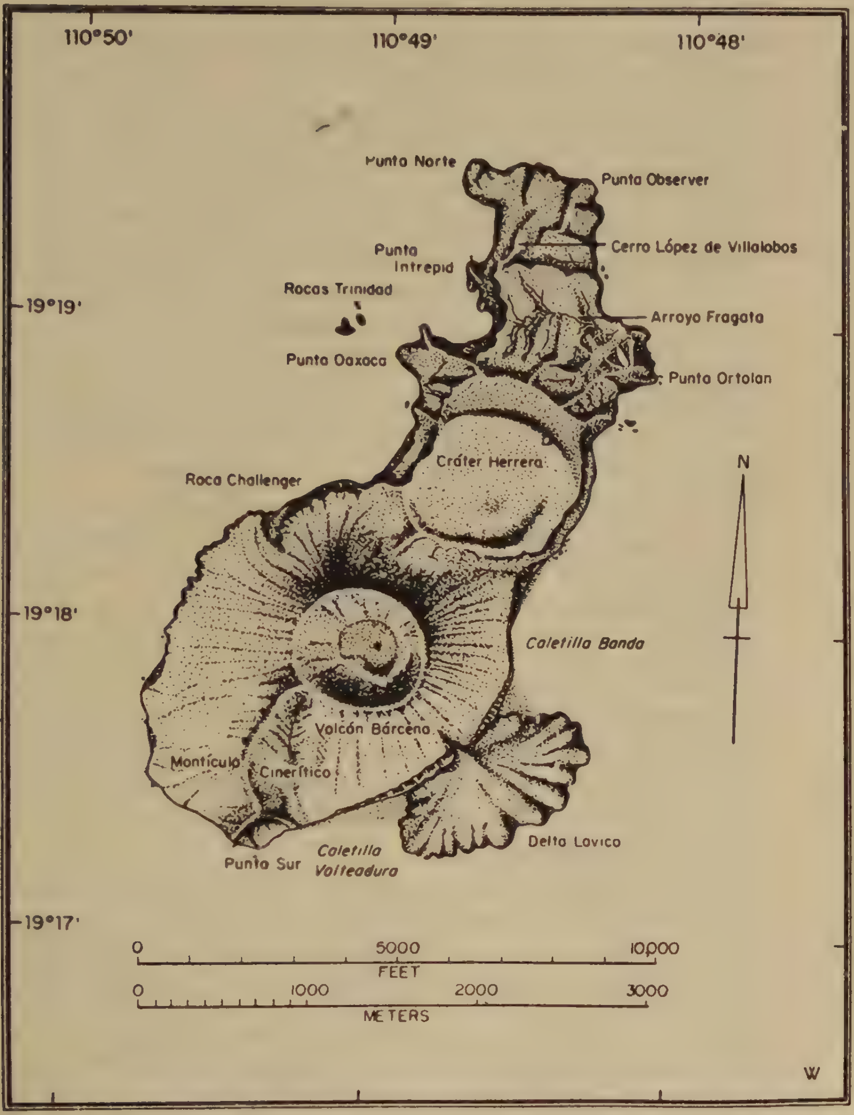
110°50'
110°49'
110°48'
19°19'
19°18'
19°17'
Punta Norte
Punta Observer
Cerro López de Villalobos
Punta Intrepid
Rocas Trinidad
Arroyo Fragata
Punta Oaxaca
Punta Ortolan
Cráter Herrera
Roca Challenger
N
Caletilla Banda
Volcón Bárceno
Montículo
Cinerítico
Delta Lavico
Punta Sur
Caletilla Volteadura
0
5000
10000
FEET
0
1000
2000
3000
METERS
W

Fig. 2. - Map of Isla San Benedicto.

who was in charge of the Galápagos expedition of the School of Tropical and Preventive Medicine, College of Medical

Evangelists. Captain Erlin Perriera, M/V *Star of the Sea*, and Captain Frank Valin, Jr., M/V *Columbia*, befriended and transported us when hitch-hiking by tuna clipper back to California from San Benedicto.

Captains Robert C. Newbegin, Laurence E. Davis, and Robert B. Haines, officers, and crew of the Scripps Institution of Oceanography's Research Vessels *Paolina T*, *Crest*, and *Stranger* worked long hours and cooperated in every way on the cruises to the Islas Revillagigedo in 1953, 1955, and 1957.

The Office of Naval Research sponsored all of the flights to Isla San Benedicto between 1953 and 1956. I express my appreciation to the officers and men of the U. S. Navy Utility Squadron Seven, Patrol Squadron Forty-six, and, particularly, Photographic Squadron Sixty-one, which flew eight completed missions, for their cooperation and willingness to help, at times under adverse conditions and personal danger.

I am very grateful to Dr. Robert S. Dietz of the U. S. Navy Electronics Laboratory in San Diego for early guidance, continued encouragement, and for the use of his unpublished reports. Prof. M. N. Bramlette of the Scripps Institution of Oceanography helped arrange for financial support in January 1953 so that I could devote nearly full time to this investigation. Prof. Howel Williams of the University of California, Berkeley, kindly contributed notes made on the September 20, 1952, flight to San Benedicto and has given me helpful advice.

A preliminary manuscript of this paper was read by Drs. Cordell Durrell, University of California at Los Angeles, and Gordon A. Macdonald, University of Hawaii. Drs. Helen Foster and Arnold Mason of the U. S. Geological Survey, Dr. A. G. MacGregor of H. M. Geological Survey, and Dr. M. Neumann van Padang of The Hague read the final manuscript. I am grateful to these people for their helpful comments and suggestions.

To my wife Joan I am deeply appreciative of her editorial advice and unstinted help.

Effect of the eruption on the fauna and flora

The indigenous fauna of Isla San Benedicto before the eruption in 1952 consisted of a single species of terrestrial song bird (the San Benedicto rock wren), sea birds, land crabs, and insects, the most noticeable of which were giant grasshoppers (HANNA, 1926, pp. 63-66). A number of migratory birds also visit the island (BRATTSTROM and HOWELL, 1956). Although the San Benedicto rock wren was seen in December, 1952, by Lewis WAYNE WALKER, it was not seen on any of the later trips and is presumed to be extinct (BRATTSTROM and HOWELL, 1956, p. 110). The remaining birds, crabs, and grasshoppers, which were nearly exterminated by the eruption, began to repopulate the island in 1953. Bats were seen at dusk in 1955, but it is not known whether or not they are indigenous. The marine invertebrate fauna is little known.

Prior to the eruption the most common land plants were grasses and a species of *Euphorbia* (HANNA, 1926, p. 63). The eruption killed nearly all of the plants of the island and of the ten previously recorded species only six were found still living in November, 1953 (MASON, 1953). *Euphorbia* was the most common post-eruption plant at that time. In March, 1957, fewer plants were found on San Benedicto than on the previous visit in May, 1955. Erosion of Bárcena ash and the pre-Bárcena surface by rain and wind has removed a large proportion of the plants which survived the 1952 eruption and were observed to be beginning to revegetate the island in 1953. If the present rate of plant destruction continues, San Benedicto may be a desert island without higher plants within a very few years.

The marine plants of San Benedicto have been described by DAWSON (1954), who collected algae from the newly formed Delta Lávico and elsewhere on the island in November, 1953.

Geological setting

Isla San Benedicto is located near the intersection of the east-west trending Clarió fracture zone (MENARD, 1955, pp. 1167-1170) and the north-south trending submarine mountain range which extends from slightly north of San Benedicto nearly to Clipperton Island (RICHARDS, 1956, 1957). Isla Clarión and possibly Isla Roca Partida (Fig. 1) appear to be related to the Clarión fracture zone, which extends over 2200 nautical miles west of San Benedicto and east to the mainland, and includes the trans-Mexico volcanic axis of Colima, Parícutin, Orizaba, and other volcanoes. Isla San Benedicto and Isla Socorro, 27 miles to the south, are located on the northern end of the range normal to the fracture zone and appear to be younger in age than the islands to the west. All of the Islas Revillagigedo are volcanoes which have built up from the ocean floor.

On San Benedicto volcanism appears to have progressed south along a narrow submarine ridge which extends over 20 miles north of the island. The island is composed of pyroclastic cones, eroded domes, and lava flows and tuff deposits which are not part of a recognizable structure. Volcán Bárcena erupted on the north flank of the eroded pyroclastic cone of Montículo Cinerítico (Pl. I). Cráter Herrera, northeast of Bárcena, probably is the remnant of the crater dome of a large pyroclastic volcano, the cone of which has been entirely eroded by waves.

The rocks of San Benedicto are alkali-calcic. Soda trachyte is the most abundant. Olivine trachybasalt is the least silicic lava collected on the island and soda rhyolite is the most silicic. The lava and essential pyroclastics erupted during the formation of Bárcena are composed of soda trachyte. Little differentiation of the Bárcena magma occurred during the eruption.

There is no historical record of any previous volcanic activity on San Benedicto. However, several historic eruptions are reported to have occurred on Isla Socorro (RICHARDS, 1956), which may be the younger of the two islands.

Visit to San Benedicto in 1952 prior to the eruption

Fortunately Isla San Benedicto was visited a few months before the birth of Bárcena. In February and March, 1952, the Canadian yacht *Marijean* stopped briefly at San Benedicto for sport fishing and BATES (1952) took a photographic panorama of the southeast portion of the island from Punta Sur to northern Cráter Herrera (Pl. II, fiig. 1). These photographs show little change compared to a nearly identical panorama taken in 1925 by the California Academy of Sciences (Pl. II, fig. 2).

Photographs of San Benedicto taken in 1905 and 1925 by the California Academy of Sciences, in 1939 by Mr. Guy SILVA, and in 1952 by Mr. BATES indicate it is unlikely that volcanic activity occurred during this period.

Birth of Bárcena and activity from August 1 to 5, 1952

Sources of information.

The birth of Bárcena was witnessed by the crew of the tuna clipper M/V *Challenger*. The following is an account compiled from a telephone interview with Captain Joseph DA LUZ (DIETZ, 1953, pp. 24-25) and from personal interviews by the writer with Mr. Frank RODRIQUES, navigator, and Mr. Robert PETRIE, fisherman. Statements by these men have been supplemented with a study of a magnificent series of eight photographs of the birth of the volcano taken by PETRIE and three photographs taken by RODRIQUES.

Observations.

The *Challenger* arrived at Isla San Benedicto about 0530 (2) hours on August 1, 1952. Fishing commenced shortly after arrival in an area about two miles west of Punta Norte. About 0745 the eruption suddenly began as a white, thin, pencil-like column rose skyward behind Roca Challenger (3), According to DA LUZ rumblings were heard; PETRIE said the eruption began without sound. A few minutes later the steam column had largely dissipated and a dark gray-black or cement-colored column of ash and steam shot skyward (Pl. III). It did not appear incandescent. Almost immediately the eruption cloud began to spread laterally at the base. Impeded by Cráter Herrera to the north and Montículo Cinerítico to the south, the cloud was first seen from the *Challenger* as it spread west between Roca Challenger and Montículo Cinerítico. In the short time that the extension of the cloud pushed through the pass between the hills, another portion overtopped the junction of Cráter Herrera and Roca Challenger and reached Cerro López de Villalobos (Pl. IV). At this time a dense cauliflower plume had reached an altitude of about 4300 feet above sea level, based on an altitude of 500 feet for Roca Challenger in the foreground, and its horizontal extent was nearly 6700 feet. About 0805, twenty minutes after the beginning of the eruption, all of San Benedicto, with the exception of the Rocas Trinidad and the extreme north end, was obscured from view (Pl. V). This photograph shows that the base of the eruption cloud was rapidly expanding laterally. It had an approximate altitude of 1200 feet at Roca Challenger and about 2000 feet south of Montículo Cinerítico and at Cerro López de Villalobos. The vertical column appears to have ascended no higher than 4500 feet at this time, while the north-south extent was approximately 11,000 feet.

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(2) All times given in this paper refer to Pacific Standard time.

Several inches of powdery dust, ash, and cinders (up to about 12 mm in diameter) fell upon the deck of the *Challenger* as it headed away from the violently erupting volcano at full speed. The ocean, previously clear and blue, became turbid, due to suspended ejecta, and remained murky. Splashes in the sea southwest of Montículo Cinerítico indicated that bombs or blocks were ejected at the time the ship left San Benedicto. The *Challenger* reached Isla Socorro, 27 nautical miles to the south, about noon. A column of dark ash from San Benedicto appeared to be rising very high into the sky and dust continued to fall on the ship. In the afternoon the *Challenger* left Socorro for Roca Partida, 60 miles to the west; on the way large pieces of pumice were seen floating on the water. The eruption plume was estimated to rise higher than 10,000 feet, as seen from Roca Partida, and dust still fell on the deck of the ship. At night on August 4 or 5, flashes of light from Bárcena were seen from Socorro, to which the ship had returned.

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(3) Named after the M/V *Challenger*.

(1132)

Da Luz notified the U. S. Navy Hydrographic Office of this eruption shortly after it began and a very brief statement appeared in the Hydrographic Bulletin of August 9 (U. S. Navy Hydrographic Office, 1952). Regrettably volcanologists appear to have been unaware of the activity until August 27, when R. S. Dietz read about it in the *Los Angeles Examiner*.

Discussion.

It is unlikely that the eruption began before the *Challenger* arrived at Isla San Benedicto. The initial photographs of the eruption taken by Petrie and Rodriques from the west side of the island show that the outline of San Benedicto was unchanged compared to a 1939 photograph of the same locality taken by Silva. The crew of the *Challenger* reported that the water in the vicinity of San Benedicto was clear before the eruption; there have been no observations of clear water around the island since the eruption.

A sketch map of San Benedicto before the eruption is shown in Figure 3. This map was prepared from photographs taken from the sea before the eruption and the map shown in Figure 2. The probable location of the vent, marked by an X on Plate I, was on the north flank of Montículo Cinerítico several hundred yards inland from shore. The thin, pencil-like white vapor column at the beginning of the activity may have represented the volatilization of ground water in the porous, ashy strata of Montículo Cinerítico — a

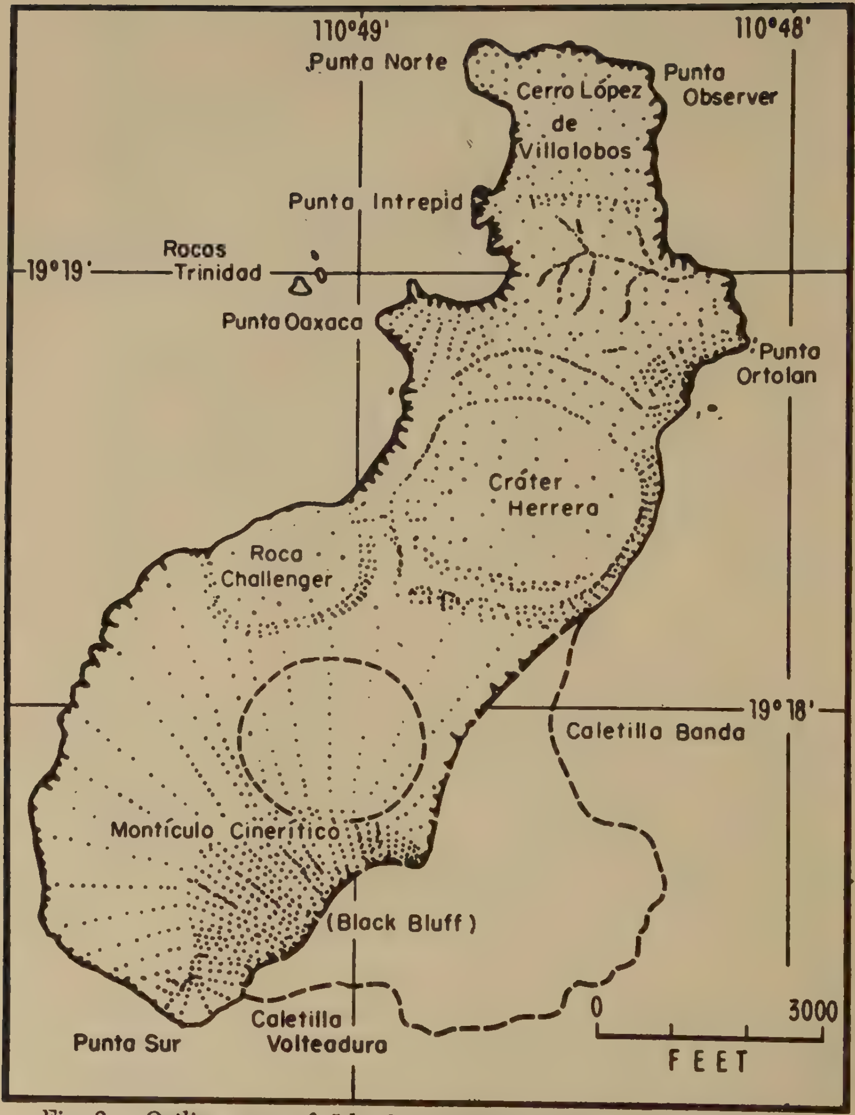
110°49'
110°48'
Punta Norte
Cerro López de Villalobos
Punta Observer
Punta Intrepid
Rocas Trinidad
19°19'
Punta Oaxaca
Punta Ortolan
Cráter Herrera
Roca Challenger
19°18'
Caletilla Banda
Montículo Cinerítico
(Black Bluff)
Punta Sur
Caletilla Volteadura
0
3000
FEET

Fig. 3. - Outline map of Isla San Benedicto, before the eruption of Volcán Bárcena. Rim of Bárcena crater and new shoreline shown by the dashed line.

phreatomagmatic explosion (Stearns and Vaksvik, 1935, pp. 15-16). If the eruption had occurred offshore it is likely that more steam would have been generated.

The most striking feature of the birth of Bárcena was the behavior of the eruption column. Its horizontal spread increased much more rapidly than its vertical rise (Table 2) and resembled the base surge of an atomic explosion (U. S. Government Printing Office, 1950, pp. 41-44, 103-110).

Table 2.

Configuration of initial Bárcena eruption column

Illustration	Maximum altitude of eruption column in feet	Maximum lateral extent of eruption column in feet	Ratio of width to height
Pl. III	2300	1200	0.5
Pl. IV	4300	6700	1.5
Pl. V	about 4500	about 11,000	2.7

Formation of the cone and activity from August 12 to September 20, 1952

Sources of information.

On August 12 Isla San Benedicto was visited by the tuna clipper M/V *Intrepid* and its seaplane. Dietz later interviewed the pilot, Mr. Chester Blasko, and compiled a mimeographed report, part of which has been published (1953, p. 27). This report has been supplemented by the writer with a study of two 16 mm Kodachrome motion picture films that were taken from the air, and an interview with Mr. Ted Howell of the *Intrepid*. The visit by the *Intrepid* is the only source of information on the activity of Bárcena between August 5 and September 12.

Largely through the efforts of Dr. Gifford Ewing of the Scripps Institution of Oceanography, two B29 flights to Isla San Benedicto from Sacramento, California, were arranged with the Fifty-fifth Strategic Reconnaissance Squadron of the U. S. Air Force. The squadron was engaged in flying daily weather flights over the Pacific Ocean so that by diverting the flights somewhat it was possible to accomplish both the weather mission and reconnoiter the activity of Bárcena. The flights took place on September 12 and 20. The scientific personnel present is listed in Table 1. An account of these two flights has been published by Dietz (1953, p. 26) and Williams (1952). Their reports have been augmented by a study of air photography taken on the flights.

Observations.

In response to a radio report of the eruption from the *Challenger* the *Intrepid* proceeded to San Benedicto, arriving at 0300 on August 12. Bárcena was in continuous violent eruption, emitting a thunderous roar. No incandescence was seen; however, a dense pall of ash and steam greatly reduced visibility. In order to prevent contamination of the ship's bait tank by floating pumice, which discolored the water to a distance of fifteen miles around the island, the *Intrepid* continued on to Isla Socorro. Here the eruption column could be clearly seen and its altitude was measured by sextant angle to be greater than 10,000 feet. The eruption cloud was estimated to extend 150 nautical miles from San Benedicto and rain was falling from it.

Blasko flew to San Benedicto from Socorro in the fish-spotting Piper Cub seaplane of the *Intrepid* between 1000 and 1100 on the 12th. The eruption was observed very close to the eastern or lee side of the volcano from an altitude of about 1800 feet. The roar of the eruption was clearly heard above the noise of the plane's motor. A cone of dust and ash was estimated by Blasko to be about 1000 feet high and the crater about 1000 feet across. Very dense volutes of yellow-gray ash and steam, which directly above the crater appeared like a bundle of asparagus, appeared to rise indefinitely skyward from the crater. Occasional small eruption clouds or volcanic density flows spilled over the rim and rushed down the side of Bárcena (Pl. VI); they sometimes reached the sea. « Rocks as large as the galley » were ejected

(1136)

which reached an estimated altitude of 2000 feet above sea level; they appeared to bury themselves upon landing on the cone.

The B29 on the flight of September 12 arrived at San Benedicto about 1300. The intensity of the activity was greatly reduced compared to that of August. During the hour at the island three yellowish-gray explosion clouds were seen at about 20-minute intervals. Each lasted 5 to 10 minutes and was composed of a stubby vertical column of ash and steam with a cauliflower texture (Pl. VII). The eruption clouds did not rise much higher than 2000 feet above sea level (4). A motion picture film taken on the flight shows that lava did not appear to be present in the bottom of the crater. A peculiar furrowing was present on the sides of the cone (Pl. VIII). The wind was from the southeast. No large blocks or bombs were ejected during the time that Bárcena was under observation and no large rocks were observed on the cone, which appeared to be entirely composed of pumiceous ash. The island was covered by a thick blanket of ash, which was ripplemarked on Roca Challenger.

On the B29 flight of September 20 the sky was comparatively free of clouds and a large number of excellent photographs were taken of the island. The cone was estimated by Williams to be 1500 feet high. No ash was discharged during the hour and one-half visit. Puffs of steam, and a little hydrogen sulfide, rose a few hundred feet above the crater rim at intervals of a few minutes and steam issued from many small vents around a dome of blocky lava at the bottom of the crater (Pl. IX). The vapour pressure of the steam was estimated to be only a few atmospheres.

Heavy rains had fallen on the island since the previous flight, establishing a drainage pattern, and ponded water was present in Cráter Herrera. Large pumice rafts were observed around the island, apparently formed from material eroded by rains or by wave erosion.

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(4) Erroneously reported to be 2800 feet above the crater rim in an earlier paper (Richards and Dietz, 1956, p. 158).

Discussion.

There is some question about the altitude of the cone during this period. Dietz (1953, p. 27) compared photographs taken on the two September flights and stated that there had been no noticeable change in the form or size of the crater; no altitudes were given. Williams (1952) wrote that on September 12 (September 13 is given in his paper) the cone was 1000 feet high and almost a mile across at the base and on the 20th it was 1500 feet high. A study of the August 12 films and September photography by the writer indicates that there was little change in the altitude of the cone after August 12 and that it was about 1100 to 1200 feet high. The rapid growth of Bárcena is in agreement with the statement by Williams (1952) that almost surely most of the new cone was built during the first few weeks. The estimate by Blasko that the crater rim was only 1000 feet in diameter in August appears to be low by a factor of two.

Air photographs taken in September show that a terrace, formed from tephra (5) fill and about 300 feet wide, was present in the southwest side of the crater (Pl. IX). Vulcanian explosions diminished in intensity in late August or early September with a resulting decrease in the size of the crater on the leeward side. In this area the gentle declivity reduced the tendency for internal landslides to keep the rim sharply edged and subsequent tephra deposition rounded the rim. The northeast rim was still so sharp in December that it was impossible to walk along it without straddling the rim.

Dietz (1953, p. 27) described the appearance of steam, issuing from small vents around the dome, as a coronet (Pl. IX). The nature of the Bárcena coronet appears sufficiently similar to the phenomenon witnessed at Santorini to be called by the technical name « coronet », which was proposed by Washington (1926, p. 369).

The depth of the crater was determined photogrammetrically from vertical air photographs taken on the September 20 flight. Photographs from two flight lines were examined using a stereocomparagraph (McNeil, 1952, pp. 608-622). Differences in spot altitudes were averaged in order to reduce errors resulting from tilt present in the photographs. Vertical control was based on sea level and an altitude of the crater rim obtained from a topographic map.

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(5) A collective term for all fragmental volcanic material ejected through the air from a volcano (Thorarinsson, 1944, p. 210; 1956, p. 20).

The crater floor had a computed altitude of about 420 feet above sea level. Assuming a maximum altitude of 1100 feet for the rim, the crater was nearly 700 feet deep. On the September 20 flight Dietz (Richards and Dietz, 1956, p. 160) visually estimated that the crater was 700 feet deep. The dome on the crater floor was about 25 feet high and 180 feet in diameter. Maximum width of the crater rim, determined later by photogrammetry, was about 2300 feet.

Solidified lava in the vent indicated the end of the first period of activity of Bárcena. Because no reports from fishermen were received until early November, the volcano appears to have entered a period of repose which lasted until enough pressure was generated to extrude additional lava into the crater.

Crater activity from November 12, 1952, to February 27, 1953

Sources of information.

Radio reports from fishermen of renewed activity at Bárcena were received at the Scripps Institution of Oceanography in November, January, and February (see Table 1). Additional reports were obtained by radio and interview during the time the writer visited San Benedicto on the yacht *Observer* in mid-December. On November 15 the writer made his first visit to San Benedicto on an observation and photographic flight, which was made in a PBM amphibian by Utility Squadron Seven from the North Island Naval Air Station in San Diego. Interviews in 1953 were made with Captain Paul Lynn and Mr. Jack Baker of the M/V *Cape Beverly*, and with Captain Edward Mitchell of the M/V *Columbus.* Baker and Mr. Robert Morton, of the Columbus, took photographs of the activity.

Observations.

Captain Neves of the M/V *Constitution* radioed the first report of renewed activity at Bárcena on November 12. His message stated: « Intermittent puffs of white smoke frequent at times with flame shooting above the crater. The light of flame reflecting on low clouds visible 40 miles at night ». A second radiogram reported that « smoke », which was thicker on the 13th, was seen from the south side of Isla Socorro, a distance of about 36 nautical miles. Apparently the *Constitution* returned to San Benedicto because on the 15th a message was received that when the ship was abeam of the volcano a « low rumbling » sound was heard as each puff of steam appeared above the rim of the crater.

On the PBM flight of the 15th the crater was observed to be more than half-filled with viscous lava in the shape of a dome (Pl. X). The surface of the lava did not appear incandescent. A few small, sporadic explosions of steam and a little ash occurred from the crater while the plane was flying around the island. No explosions were noted during the short time that the interior of the crater was under surveillance. A continuous weak emission of steam occurred from near the center of the dome.

On the 19th Captain Zeluff of the M/V *Paramount* reported that a radio message from the M/V *American Ladies* to him stated that three « medium-sized » eruptions spaced one-half hour apart occurred during the night of the 16th. On the 17th activity consisted of steady « smoke and steam », with minor eruptions every five minutes that produced a steam and ash column which rose to 1000 feet (presumably above the crater) and obscured most of the island.

The *Paramount* approached San Benedicto on the 19th and radioed the following message:

« Volcano first observation 25 miles. Minor eruption fre-

(1140)

quency 2 ½ minutes. Duration frequency largest eruptions averaged 40 to 45 seconds. Smaller eruptions averaged 12 to 17 seconds. Plane followed large to smaller eruptions. Only largest contained smoke or discoloration. Between eruptions starting and stopping are abrupt. Between smaller they are diffused. Would consider actions minor at present ».

Zeluff later told the writer that the eruptive activity occurred about every 45 minutes and at night incandescent boulders were hurled 100 to 200 feet above the crater rim. They appeared to fall back into the crater.

No further reports were obtained in November. On December 4 Captain Perreira of the M/V *Star of the Sea* witnessed essentially the same type of activity as described by Zeluff on November 19. However, eruptions of dark-colored steam and ash, which rose 100 to 200 feet above the crater, occurred about every 20 minutes. Perreira did not see any dark-colored eruptions on a visit to San Benedicto on December 8.

At 1930 on the night of the 8th, Captain Carmelo Marino of the M/V *Santa Margarita* reported that « fire came out of the crater » and five blasts occurred between 2300 and 0030 on the 9th. The observations were made from about ten miles west of San Benedicto. (The « fire » was probably reflection of light from incandescent crater lava on low clouds or steam from the crater and presumably the blasts were due to explosions in the dome).

During the afternoon of December 9 two kinds of crater eruptions were noted by the writer as the yacht *Observer* approached Isla San Benedicto from the northwest. The first consisted of white clouds of steam erupted every few minutes which lazily rose only a few hundred feet above the crater rim before dissipating. The second consisted of small, darker, poorly-defined cauliflower eruptions of steam with a little ash, which erupted on an average of every 40 to 50 minutes. They commonly ascended about 3000 feet above sea level before the top of the column was flattened by the prevailing northerly wind. A rumble of about five seconds duration preceded some eruptions of steam and ash from the crater during the evening of the 9th (Lewis W. WALKER, personal communication).

The crater was entered by WALKER and the writer on December 10. The lava dome had altered since November 15; instead of a single structure it was composed of two parts consisting of an outer doughnut-shaped dome of brownish-black, older lava and, in the center of the outer doughnut, an elliptical dome of fresh-appearing black lava. An annular depression or « moat » separated the inner and outer part of the dome (Pl. XII). The older lava was surfaced with fragmented lava rubble; the younger had no noticeable rubble. Breadcrust bombs and lava ejecta littered the ash cone and older lava. Steam eruptions, which started and stopped slowly, occurred from the western side of the moat. Darker eruptions of steam and a little ash originated from a crater vent in the middle of the black lava. They started and stopped abruptly. Weak orange incandescence periodically was visible in localized areas in the center. The west margin of the outer dome was estimated to be 50 feet high. It was coated with yellow solfataric deposits. A roar like that of a jet airplane from escaping steam emanated from a solfatara amid a jumbled cluster of lava boulders south of the inner dome. The noise in the crater sometimes was loud enough to require shouting to a person standing nearly. South of the outer dome, solfataric activity had excavated two craterlets on the floor of the main crater between the outer dome and the side of the cone with estimated depths of over 30 feet and rims about 100 feet in diameter. Their size, and the length of time that sufficient gas pressure existed to keep the craterlets excavated suggests that they were of primary magmatic origin.

On the lee or south side of the rim there were fresh deposits of soft, flour-like ash (Pl. XI). Edward NAPONELLI, seaman from the *Observer*, and the writer walked along the south rim to the graben area above the Delta Lávico. In places the unconsolidated ash was so soft that one would sink into it above the knees. While on the south or leeward rim, an eruption of steam occurred in the crater and quickly enveloped us. A little gritty ash was present in the steam and there was an almost overwhelming odor of burning sulfur (sulfur dioxide ?). Flecks of yellow sulfur were abundant on the inner rim and leeward wall of the crater indicating that sulfur was condensed directly from the steam eruptions.

Intermittent eruptions of ash and steam continued until the morning of December 12, when a dark cloud (described later) descended the cone at dawn. Bárcena burst into a continuous discharge of steam and a little ash after the ejection of the cloud. The eruption column rose to about 3000 feet above sea level before it was flattened by the prevailing wind (Pl. XIV).

The western crater rim has a greater elevation than the eastern rim. On december 12 this slope was measured and found to be 7 degrees. The exterior slope of Bárcena was measured and determined to be 33 degrees.

The last reports of activity in December were received from Captain Zolezzi of the M/V *St. Mary* and the Master of the M/V *Shasta* who radioed the writer (returning to San Diego on the *Star of the Sea*) that on the 13th eruptions of steam and a little ash occurred every 20 minutes until noon, when the eruptions became continuous and darker-colored compared to the color of those of the 12th.

Isla San Benedicto was visited on January 4, 5, and 12, 1953, by the M/V *Cape Beverly*. Captain Lynn later told the writer that on both visits Bárcena continuously emitted light gray steam and ash which rose to slightly over 3000 feet above sea level and extended nearly to Socorro. In the lee of San Benedicto volcanic dust fell on the ship. (It may have resulted from deflation rather than volcanic activity at that time). At Socorro there was a distinct odor of sulfur, not as pungent as hydrogen sulfide. The intensity of the odor increased when the *Cape Beverly* steamed from Socorro to San Benedicto.

Photographs taken by R. H. Morton of the M/V *Columbus* show that only intermittent puffs of light-colored steam were being erupted from the crater of Bárcena on February

27. Because no steam and ash was erupted on the March visits to San Benedicto it is probable that eruptive activity stopped by the end of February. There have been no verified reports of any activity other than solfataric steaming after the end of February, 1953.

Development of the Delta Lávico: December 8, 1952, to March 1, 1953

During this period data were obtained by radio and interview from tuna fishermen and from a visit to San Benedicto by Lewis **Wayne Walker** and the writer between December 9 and 12.

Initial development.

At 1345 on December 8, a landslide originated on the southeastern sea cliff of Volcán Bárcena half way between sea level and the top of the 160-foot cliff. It was witnessed from the M/V *Star of the Sea*, which had just arrived in the area. According to Captain Manuel A. **Silva**, additional landslides occurred during the afternoon and by 1430 a cave-like depression had formed. About 2030 (Co-captain **Perriera** believed that the time was 2105) an « enormous amount of black smoke » was either emitted from the side area or from the crater and lava began to flow from the depression in the side of the cliff. The observations were made from one or two miles east of the new vent. That night crater activity consisted of lava incandescence and audible detonations.

On the morning of the 9th brownish-colored eruptions and an occasional rumble came from Bárcena. Lava from the vent flowed down the cliff, across the beach, and reached the sea at 0830. The flow became more active at noon. Captains **Zeluff** and **da Luz** reported this activity (Table 1).

The yacht *Observer*, with the writer aboard, rounded Punta Observer (6) (Fig. 2) at 1617 on the 9th, and by 1710 Captain Charles G. **Zamora** had anchored the yacht abeam of the vent of the new flow in twenty fathoms of water 2700 feet from shore. Measurements were made of the size of the beginning lava flow by RCA CR-103 radar (Zamora), using the one mile range, and sextant angles (Richards). A tabulation of measurements on the 9th, and the next two days, is given in Table 3. The deltaic shape of the flow prompted the name Delta Lávico (lava delta) for this feature.

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(6) Named after the ship.

(1144)

At 1705 without warning white vapor began to escape from the sea cliff about 2200 feet north of the delta and it soon became apparent that a fumarole had formed at, or slightly below, sea level; no lava issued from this new vent. During the night and early morning odorless vapor from the fumarole rose as high as 300 feet and at times was dense enough to obscure the Delta Lávico; the vapor was much more abundant than steam generated at the margin of the flow by the glowing lava in contact with sea water. By the morning of the 10th a large concavity had formed in the 30-foot-high cliff and the beach was destroyed. Visible activity stopped by the morning of the 12th (7).

Above the Delta Lávico the crater rim had faulted and a small graben about 1000 feet long with a 12 to 15 foot vertical displacement had formed, probably at the time lava broke through the base of the cone. Minor vertical fractures developed *en échelon* between the lateral edges of the graben and the vent 700 feet below the rim.

The Delta Lávico was an impressive sight seen from the *Observer* before dawn on the 10th. The mouth of the vent was a bright orange color with an occasional flare of orange-white. An estimated maximum temperature of about 1200° C, based on a color scale of temperature (yellowish red to incipient white heat), was indicated which probably resulted from burning gas. Color below the mouth of the vent graded from red-orange to dull red. The top surface of the flow had cooled and was black. At the active margin of the flow the color ranged from dull to bright red, the latter color appearing when large blocks toppled off the top of the forward

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(7) In May, 1955 a very small amount of vapor was issuing from a warm spot at the base of the sea cliff in this locality.

Table 3.

Growth of the Delta Lávico: December, 1952, to March, 1953

Date	Time	Maximum altitude of vent in feet	Maximum altitude of delta below vent in feet	Width in feet	Seaward extent in feet
December, 1952					
9	0730	about 80	—	—	—
9	1700	140	45	700	700
10	0645	—	65	—	900
11	0600	190	75	1170	900
March, 1953					
9	—	260	125	see below	
April, 1953					
16	—	> 208 < 260	about 120	4240	2160

margin of the flow exposing the incandescent interior. As the lava advanced seaward a rumbling roar was produced by grinding of boulders. An especially loud rumble was usually followed by a tremendous hiss, as incandescent rock suddenly became quenched by the sea. The small amount of steam generated from these quenchings rose 30 to 75 feet above sea level in sporadic bursts (Pl. XV). Immediately seaward of the flow margin the water was little heated and it was possible to maneuver a skiff directly next to the flow and pick up samples of lava which only a few minutes before had been glowing.

Fumes from the vent were darker than the white steam from the margin of the flow (Pl. XV). No odor was perceptible on the 10th and 11th aboard the *Observer* east of the delta because a north wind was blowing. Leeward of the flow there was a faint smell of sulfur.

On the morning of the 11th the *Observer* left San Benedicto for the Islas Galápagos, and Walker and the writer were transferred to the M/V *Southern Queen*. A flight over and around Bárcena in the ship's fishspotting Piper Cub seaplane, piloted by Victor Silva, was made possible by Captain John Rippo, Jr. The concentric growth of the Delta Lávico, relation of the flow to the beach, and beginning development of lava tongues could be clearly seen from the air (Pl. XVI). A diagrammatic sketch of the flow at 0600 on this date is shown in Fig. 4.

An upset landing by skiff was made on the beach of Caletilla Volteadura (Turnover Bight) after the flight. A planned ascent of the volcano and a night camp in the crater was given up because of the loss of two cameras (Richards and Walker, 1954).

The west side of the Delta Lávico could be approached from the beach (Pl. XVII) and one could stand within a few feet of the advancing flow without too much discomfort, even though incandescence of the flow interior was clearly visible between blocks. The viscous trachyte lava advanced by boulder-sized blocks rolling from the top or front of the flow to the base. Lava boulders fell virtually at our feet on the pumice beach; they did not break apart. Several boulders,

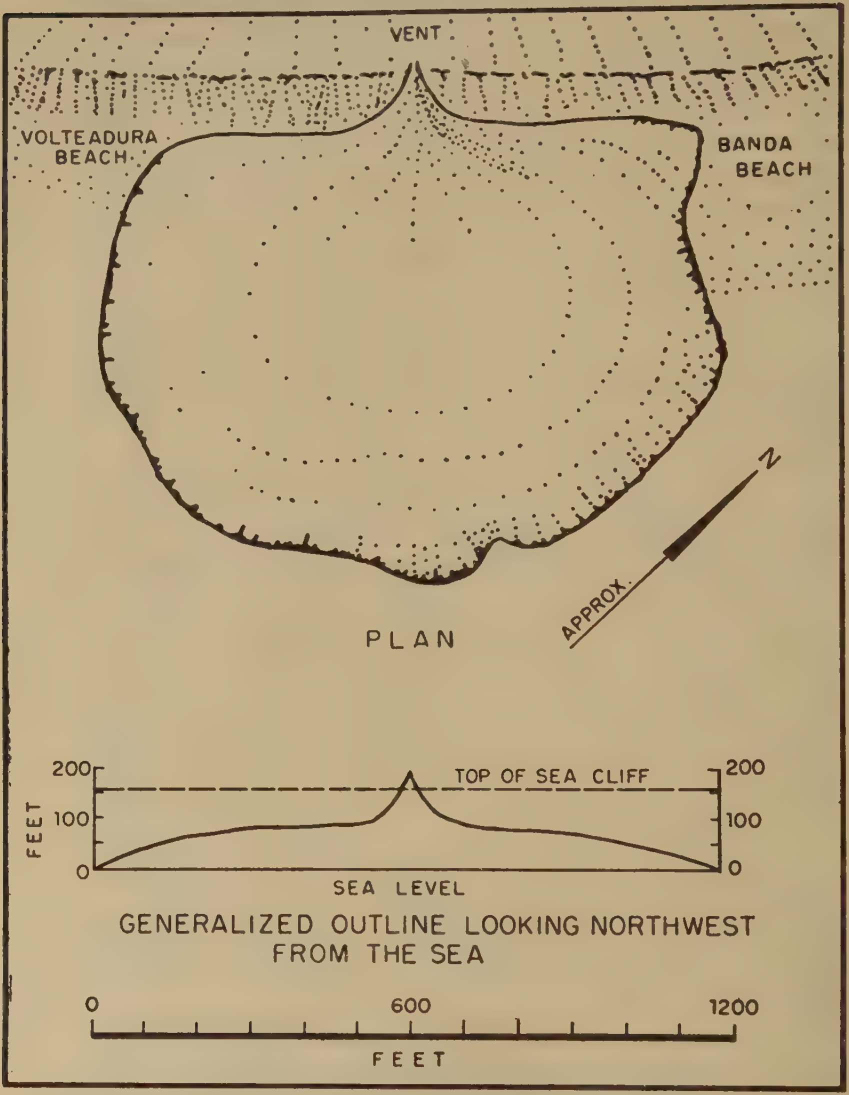

VENT
VOLTEADURA BEACH
BANDA BEACH
N
APPROX.
PLAN
200
100
0
FEET
TOP OF SEA CLIFF
200
100
0
SEA LEVEL
GENERALIZED OUTLINE LOOKING NORTHWEST FROM THE SEA
0
600
1200
FEET

Fig. 4. - Sketch of the Delta Lávico at 0600 on December 11, 1952.

three to six feet in diameter, fell into the sea near shore and two successive waves washed over them before the glow was extinguished. Occasionally it took up to one-half minute for the sea to subdue visible incandescence. During this time the boulders would steam quietly and no physical change due to fracturing or exfoliation was observed. The slope of the flow margin on land was estimated to be about 60°, appreciably steeper than the 14° seaward margin opposite the vent.

At 1800 on December 11 measured marks were made on the cliff face west of the flow margin by WALKER. By 0600 on the 12th the lava had advanced to the mark placed 40 feet from the margin 12 hours earlier.

Later growth.

The Delta Lávico was reported active on January 4-5, and 12, 1953, by Captain LYNN of the M/V *Cape Beverly*. A photograph taken by Jack BAKER on one of these visits shows that the flow had nearly reached its maximum size. Lava movement was predominantly on the north, northeast, and south sides. Photographs taken by R. H. MORTON of the M/V *Columbus* on February 27 show that the flow was only slightly active on the south side.

The R/V *Paolina T* of the Scripps Institution of Oceanography arrived at San Benedicto on March 9. There was no activity other than solfataric steaming and the flow had grown appreciably compared to December. The seaward slope had increased from 14° in December to about 40° in March. An average altitude of the flow and the height of the top of the vent was determined by means of a surveying altimeter (Table 3). The width and seaward extent of the flow in March was the same as in April. Although in early March the flow was too hot to walk on except at the outer edges, the mouth of the vent was entered in the latter part of the month by a group of tuna fishermen from the M/V *Southern Queen*, some of whom put water into their boots to keep their feet cool. The flow could be traversed in November, 1953, without discomfort. A vertical air photograph of San Benedicto taken on April 16 shows the Delta Lávico before erosion began (Pl. XVIII). The dark areas on the delta undoubtably represent the last flows of lava in January and February.

Solfataric phase: March 1953 - ?

Observations of Isla San Benedicto were made on two Scripps Institution expeditions and six U. S. Navy photographic and observation flights between March, 1953, and November, 1954 (Table 1).

On the March, 1953, visit to Bárcena solfataric activity was of two types and occurred in four different locations. The first, and most impressive, type was a weak continuation of the December activity in the craterlets south of the outer dome in Bárcena crater. Gas pressure was still sufficiently strong to keep the southeast solfatara craterlet V-shaped and clear of debris. The south craterlet had been partly filled by slumping of the crater wall. The second type of activity was a quiet emission of steam from the cooling lava in the crater, on the Delta Lávico, and in the depression area in the side of the cone above the mouth of the Delta Lávico vent.

A stereoscopic examination of vertical air photographs taken on September 21, 1953, shows that the southeast solfatara still contained a steep, V-shaped depression, indicating that it continued to be active. This solfatara is located southeast of the crater above the Delta Lávico magma conduit (Pl. XVIII).

On the November, 1953, visit the secondary solfataras in the crater emitted superheated steam (Zeller, 1953).

Vertical air photographs taken on August 6, 1954, show that the southeast solfatara was partly filled with sediment from Bárcena crater wall. Hence primary solfataric activity stopped between September, 1953, and August, 1954, and Bárcena can be considered dead as of this period. It is unlikely that the volcano will become active in the future because of the brevity of tuff-cone or tephra eruptions (Bishop, 1901).

The appearance of Isla San Benedicto today is virtually the same as shown in a photograph taken in March, 1955 (Pl. XIX).

Solfatara deposits

Samples from solfataras in Bárcena crater and above the Delta Lávico vent were collected in March and November, 1953, and studied using an X-ray diffractometer. Sulfur and halite were recognized and compared to known standards. The samples may have contained gypsum, but ammonium chloride was not found. The predominant mineral was sulfur. Solfataras often had surficial layers of encrusted sulfur over one-half inch thick. Sodium chloride may have precipitated from sea salts in the air, although the mineral halite is also known as a sublimation product (von Wolff, 1914, p. 585).

Tephra avalanches

General statement.

Volcanic eruption clouds that descend under the influence of gravity because of a greater density than air are commonly called *nuées ardentes, Glutwolken,* or glowing avalanches (clouds). They are a type of density flow. In the weaker types incandescence is not necessary but the cloud must be hot. A number of classifications of glowing avalanches have been proposed; references are listed in a recent paper by Williams (1957, pp. 59-60).

Incandescence of volcanic density flows was never witnessed at Bárcena, perhaps because all observations at close range were made during the day when the glow of liquid magma particles would tend to be obscured by sunlight, hence the term glowing avalanche appears somewhat inappropriate. In order to avoid the connotation of incandescence, when it is uncertain whether or not it existed or when it is known that it did not exist, a more general term, tephra avalanche, is proposed. Tephra avalanches can include all apparently incandescent *nuées ardentes* as well as the range of weaker *nuée ardente* phenomena including ash and/or block flows (Perret, 1937, p. 45, 65).

Avalanche of August 12.

A tephra avalanche that bulged over the crater rim and rushed down the flank of Bárcena is shown in Plate VI. The following characteristics were determined from Kodachrome motion pictures: the avalanche did not appear to be incandescent, next to the cone it appeared to have a rolling rather than a sliding motion, it descended from the lowest point on the crater rim, and there appeared to be a gaseous dilation from the center of the avalanche. Insufficient detail exists in the films to tell whether or not the avalanche furrowed the cone. During the time it was ejected from the crater a dark ash and gas column, which had the appearance of a closely packed bundle of asparagus, rose skyward from the crater in normal vulcanian fashion.

Avalanche of December 12.

On the morning of December 12 a small tephra avalanche or ash flow was witnessed at close range by Walker and the writer from the beach west of the Delta Lávico. During the previous three days Bárcena had been erupting intermittent, poorly defined volutes of gas and a little ash from the crater. At 0512 in the pre-sunrise twilight, suddenly, and without warning, a large black-appearing cloud poured over the graben area of the crater rim, rushed down the cone, crossed the Delta Lávico, and spread out to sea. Within about one minute — actually it seemed to appear almost simultaneously — the edge of the cloud passed overhead and at 0513 a shower of dust and ash fell upon us. The particles ranged in diameter from about 0.1 to 3 mm and averaged about 0.5 mm. At 0520, eight minutes after the cloud appeared, rain fell as we retreated to the west end of Volteadura Beach. Dust, ash, and water mixed to form a light rain of large muddy drops, somewhat like a hail-storm. The rain stopped at 0540. According to Captain Perreira, who was readying the *Star of the Sea* about three miles offshore preparatory to picking us up, within minutes after the beginning of the eruption the entire island, with the exception of the extreme north and south ends, was obliterated from view. However, from Volteadura Beach the Delta Lávico could be seen at all times, indicating that the dust pall was not dense. Our location at the beginning of the eruption was about 1000 yards from the graben area of the crater rim. Hence the speed of the avalanche was about 30 knots or more. It appeared to descend the slope and travel out to sea very rapidly. The wind direction, observed from the beach, was westerly or blowing in the same direction that the cloud traveled. Bárcena became continuously active after expulsion of the avalanche, belching a light-colored cloud of gas and a little ash (which appears dark in Plate XIV).

Discussion of avalanches.

The Bárcena tephra avalanches observed in August were initiated from an open crater in which it is very unlikely that lava was present. This general type of eruption, of which the Soufrière in St. Vincent is the type example, has been called *nuées ardentes d'explosions vulcaniennes* by Lacroix (1930, p. 461) and vertically initiated crateral *nuées ardentes* by MacGregor (1952, Table II; 1955, p. 4). *Nuées ardentes d'explosions vulcaniennes* are accompanied by vertically rising cauliflower clouds of ash (van Bemmelen, 1949, p. 193). Bárcena tephra avalanches of August appear to have the two essential characteristics of *nuées ardentes* according to Perret (1937, p. 48): « an extremely rapid transport of crater material in a horizontal direction to considerable distances, and a lava in itself highly explosive and continuing to discharge gas throughout its mass as long as its temperature remains sufficiently high ».

The formation of tephra avalanches at Bárcena is not surprising considering the explosiveness of the volcano. A formula for calculating the explosiveness of a volcano has been devised by Rittmann (1936, p. 162), in which the index of explosiveness is equal to the amount of loose material (ejecta) divided by the total amount of material erupted. The index for Bárcena is about 90 per cent. It is unusually high for a Pacific Ocean volcano, where the average index is only 3 per cent (RITTMANN, 1936, p. 167). Parícutin, which did not produce tephra avalanches, has an index of about 65 per cent.

The composition of the tephra contained in the avalanches presumably was the same as the soda trachyte tephra of the cone.

The tephra avalanche of December can be regarded as a decadent, vertically initiated avalanche ejected from the summit crater of a dome. Only a single avalanche is known to have been expelled and it occurred so rapidly and unexpectedly in the dawn twilight that little can be said in addition to the above narration of the experience. The avalanche definitely did not appear to be a landslide of unstable hot ash from the flank of the cone or an *avalanche produite par décollement* (LACROIX, 1906, p. 657) or hot avalanche (PERRET, 1924, pp. 89-92). It presumably originated without explosion because of the absence of warning sound.

Discussion of furrows.

Furrows which formed on the flank of Bárcena prior to September 12, 1952, have been studied by inspection of air photographs taken on the 12th and 20th. A summary of data on the furrows obtained from these photographs is compiled in Table 4.

A satisfactory hypothesis of furrow formation must account for the following features. Above the change in slope of the cone (Pl. VIII; Pl. XX; Pl. XXI): (1) appearance of the beginning furrow below the crater rim, (2) U-shape, (3) straightness, (4) parallel, non-coalescing arrangement; below the change of slope (Pl. VIII; Pl. XX; Pl. XXII): (5) increasing width down slope, (6) turbulent patterns on the cone, and (7) local deposition at the lower ends of some furrows, between Bárcena and Cráter Herrera (Pl. VIII). The following are conceivable methods of furrow formation:

Table 4.

Summary of data on Bárcena furrows

Distribution	Areal	Best developed below low areas of crater rim on east and west flank of cone. Less well developed below high areas of rim at junctions between Bárcena, Montículo Cinerítico, and Roca Challenger.		
	Vertical	From about 40-70 feet below rim to change of slope on cone, which occurs, on an average, about 500 feet above sea level. At southeast side, where there is practically no change of declivity, the furrows extend to sea cliffs.		
		Above change of slope	At and below change of slope	
Size estimate	Width	About 10-20 feet	Wider	
	Depth	About 3-10 feet	Apparently not as deep	
	Length (8)	Depends on change of slope position and location of furrow relative to higher areas of crater rim. Average length about 800-900 feet, maximum length about 1400 feet.	Variable. Where recognizable as a furrow usually only a few hundred feet long. Where change of slope is great the furrows appear to terminate abruptly (Pl. XXIII).	
Shape	Cross section	U-shaped with a tendency for crests to be wider than troughs.	Slope change gradual (Pl. XXII).	Slope change relatively abrupt (Pl. XXIV).
			Irregular, shallow, and U-shaped	See below

(8) Based on a 33° external slope of the cone and a crater altitude of 1100 feet.

Table 4 (continued)

		Above change of slope	At and below change of slope	
			Slope change gradual	Slope change relatively abrupt
Shape	Normal to length			Ridge and valley topography
	Parallel to length of furrow		Gentle asymmetrical ridge crest up slope	Steep asymmetrical ridges with ridge crest up slope
	Plan	Straight and parallel	Poorly developed herringbone pattern	Poorly developed ridge and valley topography
Characteristics	1. Length normal to crater rim. 2. Individual furrows do not coalesce. 3. Upper end of furrow develops gradually from unfurrowed area immediately below crater rim. However, it is possible that tephra fallout, when eruption clouds cross the rim, has partly or completely buried the upper ends of furrows. 4. Width of best-defined furrows show little variability, others diverge slightly down slope. 5. Boulders may be present near the upper end of furrows.		1. Where change of slope is gradual the furrow is recognizable below change of slopé. 2. Where change of slope is abrupt furrow terminates. 3. Furrows tend to coalesce. 4. Lower ends of furrows diverge down slope. 5. Turbulence patterns in ash are more intense where declivity is the greatest. 6. Furrow debris may occur at lower ends when the change in declivity is moderate.	

(1) rain erosion, (2) avalanches of bombs or blocks, (3) ash landslides from the crater rim, and (4) tephra avalanches.

Rain erosion as a method of formation can be immediately discarded because of the size of the features and absence of dentritic drainage. (However, rain erosion later modified the furrows and superposed a dendritic drainage upon them).

Furrow erosion by bombs has been observed at Parícutin Volcano. Here the orientation of the initial furrows was dependent upon the direction of travel of the descending bombs; they were often curved rather than straight (Howel WILLIAMS, personal communication). Shortly after landing the bombs tended to roll in the same channels, about two feet wide and deep, straight down the volcano (Ray WILCOX, personal communication). The beginning straightness and size of the Bárcena furrows appears to preclude this mode of formation. In addition, no accumulation of bombs or blocks has been found at the base of Bárcena; bombs were abundant at the base of Parícutin.

Bárcena furrows originate both below the sharp edge of the windward (eastern) rim and the rounded top of the leeward (western) rim. If ash landsliding took place very near the rim on the leeward side, how could newly deposited ash build up a regular appearing rim and yet not completely fill the furrows below? Similar problems would be confronted if landslides were postulated for the windward side. Landslides also presumably would occur on both sides of the rim. The scars on the interior of the crater do not show furrowing of the type exhibited on the exterior of the cone (Pl. IX).

Fewest obstacles are encountered on the assumption that tephra avalanches created the furrows. BELL (1942) has observed that turbid underflows in lakes, dust storms, *nuées ardentes*, and other dust clouds of volcanic origin exhibit much the same behavior; however, little is known about the mechanism of erosion by tephra avalanches on the comparatively steep slopes of volcanoes. Tephra avalanches usually deposit material rather than erode, but on occasion they have furrowed Montagne Pelée (Lacroix, 1904, p. 217; Perret, 1937, p. 33). The boulders present at the upper end of some of the furrows (Pl. XXI) may have been ejected from the crater independently from the emission of tephra avalanches, or perhaps they were deposited as the tephra avalanches dilated when flowing over the crater rim. Furrows on the eastern side of Bárcena extend slightly more than half-way to the base of the cone (Pl. VIII). Presumably the tephra avalanches lost their ability to erode in this region, and it is likely that the dark areas at the base of the furrows represent deposition of furrow debris.

Summary of envisioned activity.

At the birth of Bárcena on August 1, 1952, two phenomena occurred simultaneously. One component of the eruption ascended vertically as *nuées volcaniennes* (Lacroix 1930, p. 44) and the other flowed in a horizontal direction. The motivating force of lateral flow probably was a combination of base surge, auto-explosion of the incandescent ash or lava particles contained in the cloud, and horizontal trajection.

The cone grew rapidly by tephra fallout from the eruptions and deposition from the tephra avalanches. Sometime between mid-August and September 12, toward the end of the violent phase of cone formation, tephra avalanches became intermittent. Strong, vertical, vulcanian-type eruptions continued during this period. By September the tephra avalanches contained less auto-explosive material and hence were less active. Instead of rolling they probably slid and eroded, causing the formation of furrows. The avalanches tended to descend from the lowest areas of the crater rim and furrowing was most intense below these areas. Slight slope changes caused pronounced differences in the behavior of the avalanches. The greater the declivity the greater became the turbulence of the density flow, with attendant erosion and deposition.

Only one additional tephra avalanche is known to have occurred after domal extrusion of lava into the crater. It occurred in mid-December after a period of comparative repose and three days after lava had broken through the base of the cone. This avalanche may have been caused by a sudden increase of gas evolution together with a clearing of a partly obstructed conduit. At the beginning of the eruption the initial part of the hot gaseous cloud, which contained dust, ash, and perhaps conduit debris, filled the crater and overflowed the rim at the graben above the Delta Lávico. Later, gas effervescing from the magma was insufficiently heavy to descend as tephra avalanches and consequently rose in normal vulcanian-type eruption.

Development of the crater domes

General description.

In mid-September a proto-dome had formed about 25 feet high, 180 feet in diameter, with an estimated volume of 21,000 cubic feet above the floor of the crater (Pl. IX). The blocky exterior of this dome probably indicates the effusion of viscous lava rather than an upheaved conduit plug.

Active extrusion of lava into the crater occurred on, or perhaps before, November 12. Lava more than half-filled the 700-foot-deep crater by the 15th and formed a dome, which was approximately 1200 feet in diameter and had an estimated volume of 200 million cubic feet above the crater floor of mid-September. The following features of the dome were observed by stereoscopic examination of the November 15 oblique air photographs (Pl. X): (1) the top of the dome was convex, (2) its sides were steep, (3) no talus was visible on the north, east, and west sides — the south side was not photographed, (4) its top surface had more than one raised concentric ridge, (5) a summit depression was present, (6) two tumuli were located west and south of the depression, (7) at the base of the dome there were localized fumarole deposits, and (8) steam eruptions appeared to originate from the summit depression.

Additional lava was extruded into the crater between

November 15 and December 10 forming a second dome in the center of the first, which was slightly enlarged. This

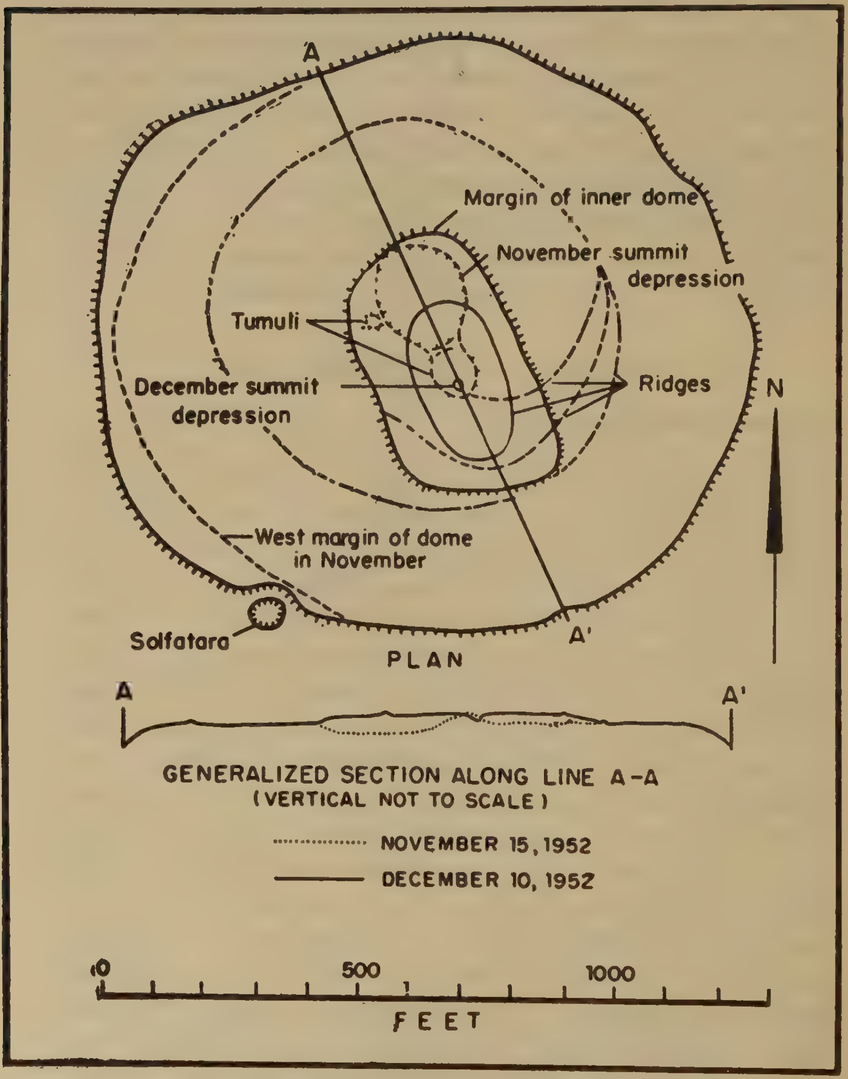

A
Margin of inner dome
November summit depression
Tumuli
December summit depression
Ridges
N
West margin of dome in November
Solfatara
A'
PLAN
A
A'
GENERALIZED SECTION ALONG LINE A-A
(VERTICAL NOT TO SCALE)
NOVEMBER 15, 1952
DECEMBER 10, 1952
0
500
1000
FEET

Fig. 5. - Sketch of Bárcena crater domes on November 15 and December 10, 1952.

second or inner dome had an elliptical shape with a 570 foot northwest major axis and a 300 foot northeast minor axis.

Its height was about 10 to 20 feet above the outer dome. An estimation of volume is difficult; 2 million cubic feet was calculated using the formula of an elipse for determining the area and 15 feet for the altitude. The fresh appearance of the inner dome on December 10 (Pl. XII) indicated that it was probably extruded in early December rather than in November. It likewise had a summit depression and, except for the absence of tumuli and only one raised ridge, was similar to the outer dome of November 15.

A diagrammatic plan and cross-section of the writer's interpretation of the appearance of the domes on November 15 and December 10 is shown in Figure 5.

The cone-shaped depression of the inner dome was first examined in the field in November, 1953. It was over 30 feet deep and there was a higher proportion of block lava (FINCH and ANDERSON, 1930, p. 249; FINCH, 1933) in it than anywhere else on the volcano.

Envisioned activity of dome development.

The following sequence of activity of dome development at Bárcena is envisioned by the writer: When the cone-building phase stopped in the middle of September an endogenous small dome was extruded from the conduit orifice before solidification of the upper conduit magma. The lack of reports from the tuna fleet before November 12 probably indicates that the active phase of extrusion did not occur until about the 12th. Bárcena crater was half-filled with a dome of viscous trachyte by the 15th. However, by this date the side of the dome had cooled (indicated by the presence of fumarole deposits) and it is possible that the dome formed before the 15th. It undoubtably grew rapidly. A vertical growth of about 350 feet in a few days is not inconsistent with figures cited by WILLIAMS (1932, pp. 141-142).

The extrusion of the first or outer dome in November may have been endogenous in the beginning, with the subsequent formation of a summit depression by collapse or explosion; it may have been entirely exogenous with a summit crater continually present; or perhaps initially the dome was endogenous and later became exogenous. Insufficient data are available for a definite answer. Breadcrust bombs, blocks of crater lava, gas, and a little ash were expelled from the vent during the later stages.

In early December magma again rose in the conduit and formed a second or inner dome in the summit depression of the first. The inner dome also had a summit depression and was probably formed by exogenous growth. Later explosions or collapse may have tended to break up the viscous, partly solidified lava in the summit depression with the formation of block lava.

On December 8 lava broke through the base of Bárcena cone and flowed out to sea. This extrusion produced withdrawal of magma from the crater, which resulted in subsidence of the domes. However, the margin of the outer dome had solidified and consequently settled very little, if at all. It was left with prominent positive relief compared to the central part, which sagged and became saucer-shaped (Pl. XIII). (A similar origin is postulated for the depressed top of Cráter Herrera - figure 2). The minor scarp on the east side of the inner dome summit depression probably formed during this subsidence.

The break-up of the surface of the outer dome undoubtably took place before and during extrusion of the inner dome; the surface of the latter fragmented between December, 1952, and March, 1953.

Two primary solfataras developed large craterlets in the crater of Bárcena immediately south of the outer dome between November 15 and December 10, 1952. These remained active until about the fall of 1953.

Delta Lávico

General description.

Trachytic lava in the Delta Lávico is gradational between block lava and aa; it can be best described as scoriaceous block lava (Howel Williams, personal communication). Individual blocks occur up to about 10 feet in size and usually have a conchoidal fracture (Pl. XXV). On the surface of the flow they are commonly only a few feet in diameter. The flow has recently been truncated by marine erosion. A gradation from the clinker phase of small fragmented blocks on top of the flow to the massive phase, which shows columnar jointing, is clearly shown in an enlargement of a photograph taken from the bridge of the R/V *Crest* in May, 1955 (Pl. XXVI). Also shown is an intermediate phase of small cobbles and boulders of block lava with smooth polyhedral faces which grade into partly detached boulders of block lava. Local areas of block lava also are found on the flow margin.

Surface lava in the flow is moderately vesicular; vesicles range from a few millimeters in diameter, normal to the direction of flow, to 3 or 4 cm parallel to the flow direction. Some of the more massive blocks, probably from the interior of the flow, are only slightly vesicular with a vesicle size usually less than 2 mm. A small, short flow south of the vent consists of spongy lava. Here gas-rich lava was extruded from near the top of the vent, flowed south, and reached the main flow at the lower edge of the vent. Lava from this flow has a pseudo-spinosity produced by a coalescence of inflated bubbles.

Movement.

Photographs taken from the sea and air in December, January, and April, after the formation of the flow, show that lava only issued from a single vent. Lava from the vent at first spread out in the shape of a fan with concentric flow lines (Pl. XVI). Later, tongues formed at the flow margin (Pl. XVIII, XIX). There was little development of moraines, because flow tongues did not form except at the margin where they tended to diverge from one another.

Lateral movement of the flow in December appeared to be similar to that illustrated by Krauskopf (1948, fig. 3). The conchoidal appearance of the large blocks in the flow (Pl. XXV) would result from the type of motion observed at Hekla and described by EINARSSON (1949, pp. 26-30), who reports that the characteristic separation of the plastic blocks was a fracturing as if the material were solid.

Vent.

A photograph taken in November, 1953, shows the relation of the vent, the solfatara area above, and the scoriaceous block lava on the surface of the flow near the vent (Pl. XXVII). Sulfurous sublimation products from the solfatara immediately above the vent coated the side of the cone nearly 300 feet to either side of the depression area in March, 1953. A close-up of the mouth of the vent shows layers of lava deposited on the sides of the vent wall as the magma oozed out to form the delta (Pl. XXVIII). Four layers are shown. They are labeled 1-4 in this photograph. Two of these (1 and 2) slope relatively steeply and probably represent flow stages when the lava level in the vent was high and the altitude of the delta low. As the lava supplied from the vent diminished, the level of the flow gradually lowered and also tended to move in a more horizontal direction because of the greater height of the delta. Two layers (3 and 4) representing the last two lowerings can be seen on the left side of the photograph next to the flow surface. The lava blocks on the surface of the flow in the vent are larger and more angular than customarily found on the surface of the delta. They originate from the final fracturing of a very viscous, nearly solidified magma.

The mouth of the vent is not more than 10 feet wide. Although the sides of the vent appear to converge downward (Pl. XXVIII), in reality they may diverge below the surface of the flow. Regardless, the hydrostatic pressure was sufficient to extrude about 800 million cubic feet of viscous trachyte through the same hole.

Subsidence.

The maximum altitude of the surface of the Delta Lávico was determined to be 125 feet by altimetry on March 9, 1953 (Table 3). Photogrammetric measurements from the April 16 vertical air photographs indicate that the maximum height was greater than 108 feet. On the November, 1953, visit visual observation and crude measurements indicated to the writer that the flow was appreciably lower. A traverse of hand level measurements made in May, 1955, determined that the maximum altitude of the flow surface was about 75 feet. Clearly the Delta Lávico appears to have subsided 30 to 40 feet. The only other evidence of settling is from the altitude of the lava flow between the vent and delta. In March, 1953, there was a smooth slope from the flow in the vent to the delta; in November a relatively abrupt slope was present. There are no other visual indications of subsidence on the delta or to either side of the pumice beaches. However, material in these locations would be unlikely to show signs of this nature because of the covering effects produced by terrestrial erosion. It is not surprising that the delta would settle considering the effect of consolidation of the pyroclastics underneath the lava caused by an overburden of about 40 million metric tons of lava. (The latter figure was determined on the assumption that a cubic meter of lava weighs about 1.9 metric tons — Fries, 1953, p. 609. It would represent an approximate average of nearly 60 metric tons per square meter of surface.)

Volume of erupted tephra and lava

Calculations have been made of the volume of tephra and lava erupted in the formation of Volcán Bárcena (Table 5). An estimation of the volume of tephra not contained in the cone is very difficult because much of the material fell into the sea; the figures given may be conservative. Areal dimensions were determined by planimetric measurement from a topographic map.

Approximately 9500 million cubic feet (270 million cubic meters) of tephra and 970 million cubic feet (27 million cubic meters) of lava were erupted. This is an order of magnitude less than the 2000 million cubic meters of material erupted in the formation of Parícutin Volcano (*cf.* Fries, 1953, p. 611).

Table 5.

Area and volume of erupted tephra and lava from Volcán Bárcena.

Feature	Material	Area		Volume	
		million sq ft	thousand sq m	million cu ft	million cu m
Bárcena cone	Tephra	15 to 20	1400 to 1900	7000 to 11,000	200 to 310
Tephra not part of Bárcena cone	Tephra	—	—	100 to 1000	2.8 to 28
Crater dome (September 20, 1952)	Lava	0.025	2.3	0.02	0.0006
Outer crater dome (November 1952)	Lava	1.1	102	140	4
Inner crater dome (December 1952)	Lava	0.1	12	2	0.6
Delta Lávico (part of flow above sea level)	Lava	6.6	610	430	12.2
Delta Lávico (part of flow below sea level)	Lava	7.4	690	400	11.3

REFERENCES

Bates, D. H., 1952 - *Revilla Gigedo Islands, Mexico*: Portland. Privately published by the author, 44 pp.

Bell, H. S., 1942 - *Density currents as agents for transporting sediments*: Jour. Geol., vol. 50, pp. 512-547.

Bemmelen, R. W., van, 1949 - *The geology of Indonesia*: The Hague, Govern. Print. Office, vol. 1A, 732 pp.

Bishop, S. E., 1901 - *Brevity of tuff-cone eruptions*: Am. Geol., vol. 27, pp. 1-5.

Brattstrom, B. H., and Howell, T. R., 1956 - *The birds of the Revilla Gigedo Islands, Mexico*: Condor, vol. 58, pp. 107-120.

Dawson, E. Y., 1954 - *The marine flora of Isla San Benedicto following the volcanic eruption of 1952-1953*: Univ. Southern Calif. Press, Allan Hancock Found. Publ., Occas. Paper 16, 13 pp.

Dietz, R. S. (Ed. by D. C. Kelley), 1953 - *Boqueron*: Pacific Discovery, vol. 6, pp. 24-27.

———— and Richards, A. F., 1953 - *Volcanic eruption of San Benedicto Island, Mexico* (Abstract): Geol. Soc. America Bull., vol. 64, p. 1503.

Einarsson, T., 1949 - *The flowing lava: The eruption of Hekla 1947-1948*: Reykjavik, H. F. Leiftur (for the Soc. Scient. Islandica), vol. 4, no. 3, 70 pp.

Finch, R. H., 1933 - *Block lava*: Jour. Geol., vol. 41, pp. 769-770.

———— and Anderson, C. A., 1930 - *The quartz basalt eruptions of cinder cone, Lassen Volcanic National Park, California*: Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 19, pp. 245-273.

Foshag, W. F., and González R., J., 1956 - *Birth and development of Parícutin Volcano, Mexico*: U. S. Geol. Survey Bull. 965-D, pp. 355-489.

Fries, C., Jr., 1953 - *Volumes and weights of pyroclastic material, lava, and water erupted by Parícutin Volcano, Michoacán, Mexico*: Am. Geophy. Union Trans., vol. 34, pp. 603-616.

Hanna, G. D., 1926 - *Expedition to the Revillagigedo Islands, Mexico, in 1925*: Calif. Acad. Sci. Proc., 4th ser., vol. 15, 113 pp.

Krauskopf, K. B., 1948 - *Lava movement at Parícutin Volcano, Mexico*: Geol. Soc. America Bull., vol. 59, pp. 1267-1284.

Lacroix, A., 1904 - *La Montagne Pelée et ses Eruptions*: Paris, Masson et Cie, 662 pp.

———— 1906 - *Contribution à l'étude des brèches et des conglomérats volcaniques (Antilles 1902-1903, Vésuve 1906)*: Soc. Géol. France Bull., sér. 4, t. 6, pp. 636-685.

———— 1930 - *Remarques sur les matériaux de projection des* *volcans et sur la genèse des roches pyroclastiques qu'ils constituent*: Soc. Géol. France Cent., Livre Jubilaire 1830-1930, t. 2, pp. 431-472.

MacGregor, A. G., 1952 - *Eruptive mechanisms: Mt. Pelée, the Soufrière of St. Vincent and the Valley of Ten Thousand Smokes*: Bull. Volc., sér. 2, t. 12, pp. 49-74.

——— 1955 - *Classification of nuée ardente eruptions*: Bull. Volc., sér. 2, t. 16, pp. 3-5.

Mason, H. L., 1953 - *Land plants, Isla San Benedicto*, in Richards, A. F. (Ed.) *The Islas Revillagigedo investigation of November 1953*: Unpubl. manuscript.

McNeil, G. T., 1952 - *Map compilation with stereometer-type instruments*, pp. 603-622 in *Manual of photogrammetry*: Washington, Am. Soc. Photogrammetry, 2nd ed., 876 pp.

Menard, H. W., 1955 - *Deformation of the northeastern Pacific basin and the west coast of North America*: Geol. Soc. America Bull., vol. 66, pp. 1149-1198.

Perret, F. A., 1924 - *The Vesuvius eruption of 1906, study of a volcanic cycle*: Carnegie Inst. Washington, Publ. 339, 151 pp.

——— 1937 - *The eruption of Mt. Pelée 1929-1932*: Carnegie Inst. Washington, Publ. 458, 126 pp.

Richards, A. F., 1953 - *Continued volcanic activity at San Benedicto Island, Mexico*: Volcano Letter, no. 519, p. 7.

——— 1956 - *Volcanism in eastern Pacific Ocean basin: 1945-1955*: Unpubl. manuscript.

——— 1957 - *Geology of the Islas Revillagigedo, Mexico* (Abstract): Geol. Soc. America Bull., vol. 68, p. 1843.

——— 1958 - *Transpacific distribution of floating pumice from Isla San Benedicto, Mexico*: Deep-sea Res., vol. 5, pp. 29-35.

——— and Brattstrom, B. H., 1959 - *Bibliography, cartography, discovery, and exploration of the Islas Revillagigedo*: Calif. Acad. Sci. Proc., 4th ser., vol. 29, pp. 315-360.

——— and Dietz, R. S., 1956 - *Eruption of Bárcena Volcano, San Benedicto Island, Mexico*: Eighth Pacific Sci. Congr. Proc., vol. 2, pp. 157-176.

——— and Walker, L. W., 1954 - *Operation cremation*: Nat. Hist., vol. 63, pp. 56-64.

Rittmann, A., 1936 - *Vulkane und ihre Tätigkeit*: Stuttgart, Ferdinand Enke, 188 pp.

Sapper, K., 1937 - *Mittelamerika: Handbuch der regionalen Geologie*: Heidelberg, Carl Winter's Universit., Bd. 8, Abt. 4a, 160 pp.

Snodgrass, J. M., and Richards, A. F., 1956 - *Observations of underwater volcanic acoustics at Bárcena Volcano, San Benedicto Island, Mexico, and in Shelikof Strait, Alaska*: Am. Geoph. Union Trans., vol. 37, pp. 97-104.

(1168)

STEARNS, H. T., and VAKSVIK, K. N., 1935 - *Geology and ground-water resources of the island of Oahu, Hawaii*: Hawaiian Div. Hydrography Bull. 1, 479 pp.

THORARINSSON, S., 1944 - *Tefrokronologiska studier på Island*: Geog. Ann., vol. 26, 217 pp. (English summary: *Tephrochronological studies in Iceland*, pp. 204-215).

———— 1956 - *On the rhyolitic volcanic eruption in Iceland in post glacial time* (Abstract): Resumes Trabajos Pres., XX Intern. Geol. Congr., Mexico, p. 20.

U. S. Government Printing Office, 1950 - *The effects of atomic weapons*: Washington, 456 pp.

U. S. Navy Hydrographic Office, 1952 - *Volcanic activity north Pacific*: Hydrographic Bull., no. 32, August 9.

WASHINGTON, N. S., 1926 - *Santorini eruption of 1925*: Geol. Soc. America Bull., vol. 37, pp. 349-384.

WILLIAMS, H., 1932 - *The history and character of volcanic domes*: Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 21, pp. 51-146.

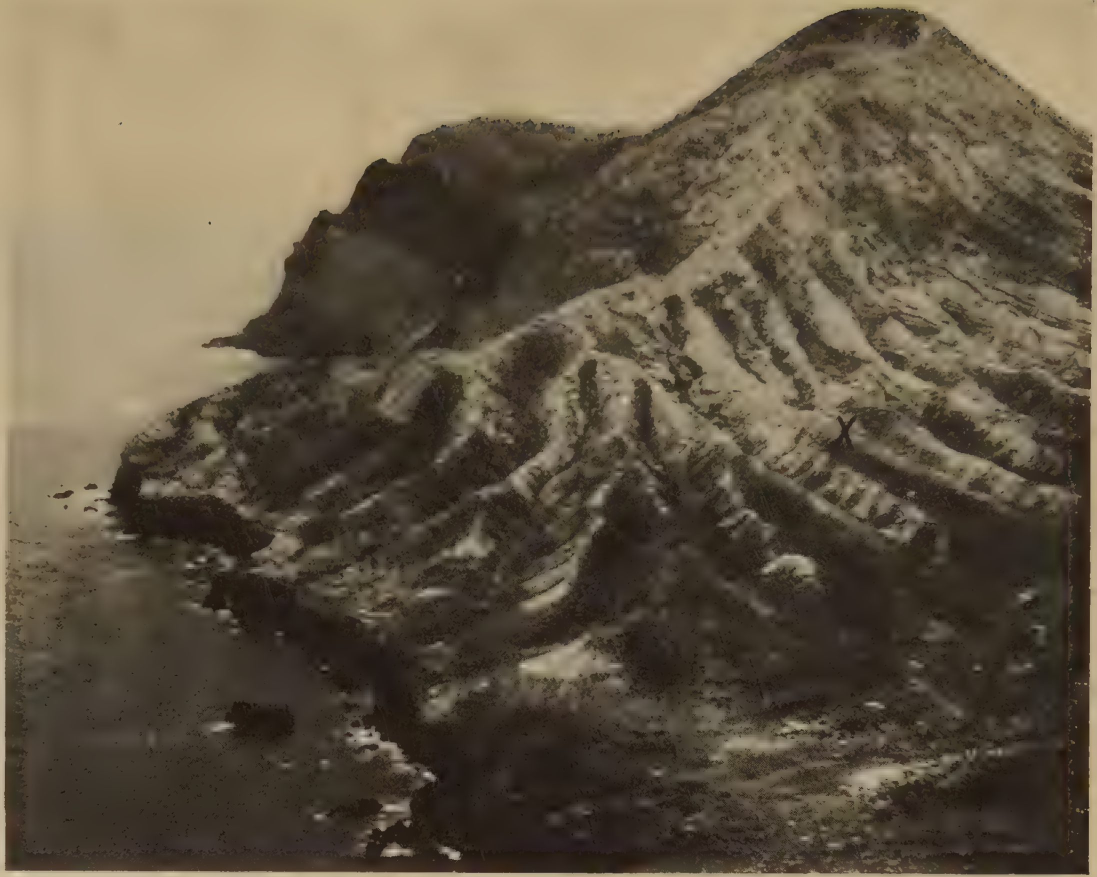
———— 1952 - *Recent eruptions on San Benedicto Island, Mexico*: Volcano Letter, no. 517, p. 7.

———— 1957 - *Glowing avalanche deposits of the Sudbury Basin*: Ontario Dept. Mines, 65th Ann. Rept., vol. 65, pp. 57-89.

WOLFF, F., von, 1914 - *Der Vulkanismus*: Stuttgart, Ferdinand Enke, Bd. 1, 711 pp.

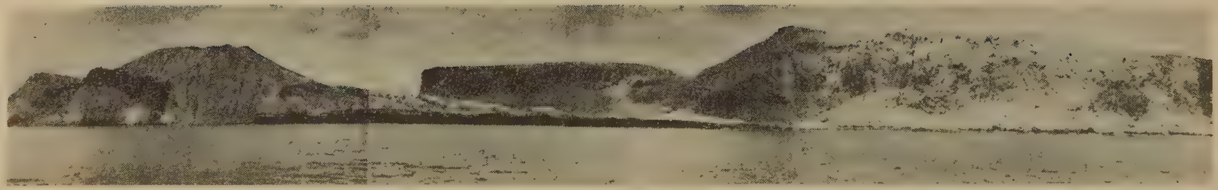
ZELLER, E. J., 1953 - *Geochemistry, Isla San Benedicto*, in RICHARDS, A. F. (Ed.) *The Islas Revillagigedo investigation of November 1953*: Unpubl. manuscript.

(1170)



North flank of the eroded pyroclastic cone Montículo Cinerítico. Probable location of Bárcena vent indicated by an X.

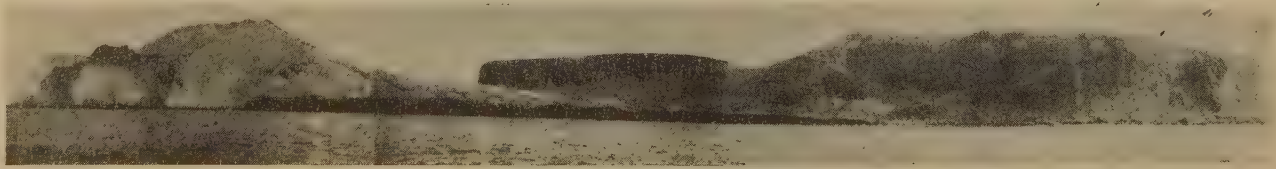
(California Academy of Sciences photo)



Panorama of southeastern Isla San Benedicto before the eruption of Bárcena.

Fig. 1. - February-March, 1952.

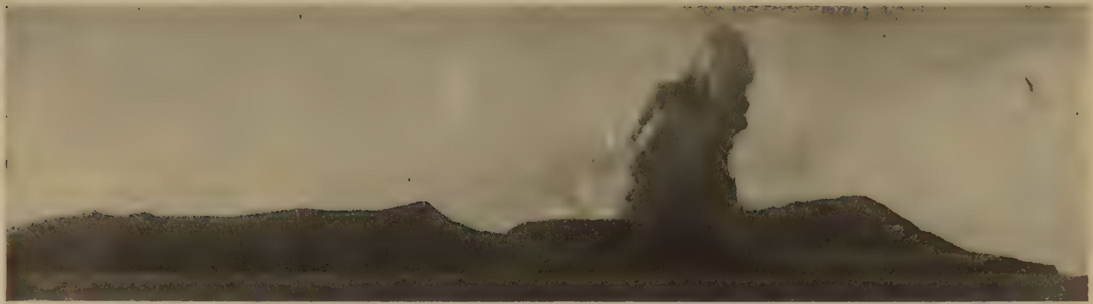
(D. H. Bates photo)



Panorama of southeastern Isla San Benedicto before the eruption of Bárcena.

Fig. 2. - May, 1925.

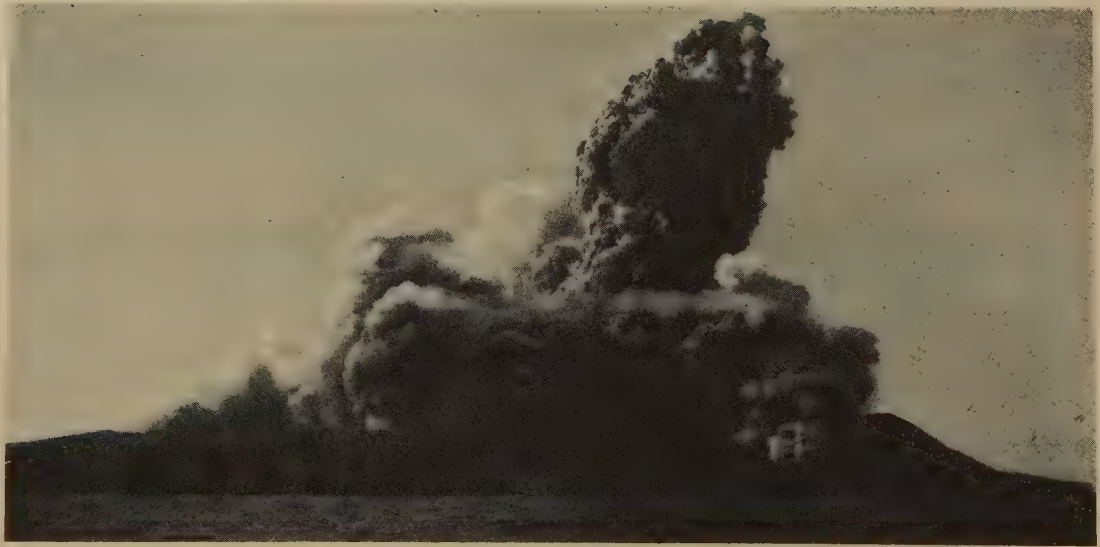
(California Academy of Sciences photo)



Birth of Volcán Bárcena.

Photograph taken from 2 miles west of Isla San Benedicto at 0745 on August 1, 1952. Cráter Herrera, left; Roca Challenger, center; Montículo Cinerítico, right.

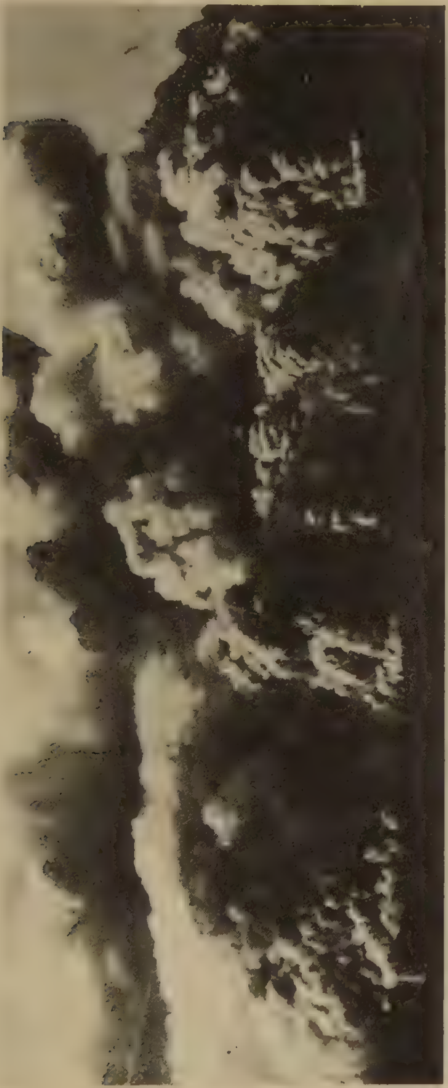
(R. PETRIE photo)



Birth of Volcán Bárcena.

A few minutes later.

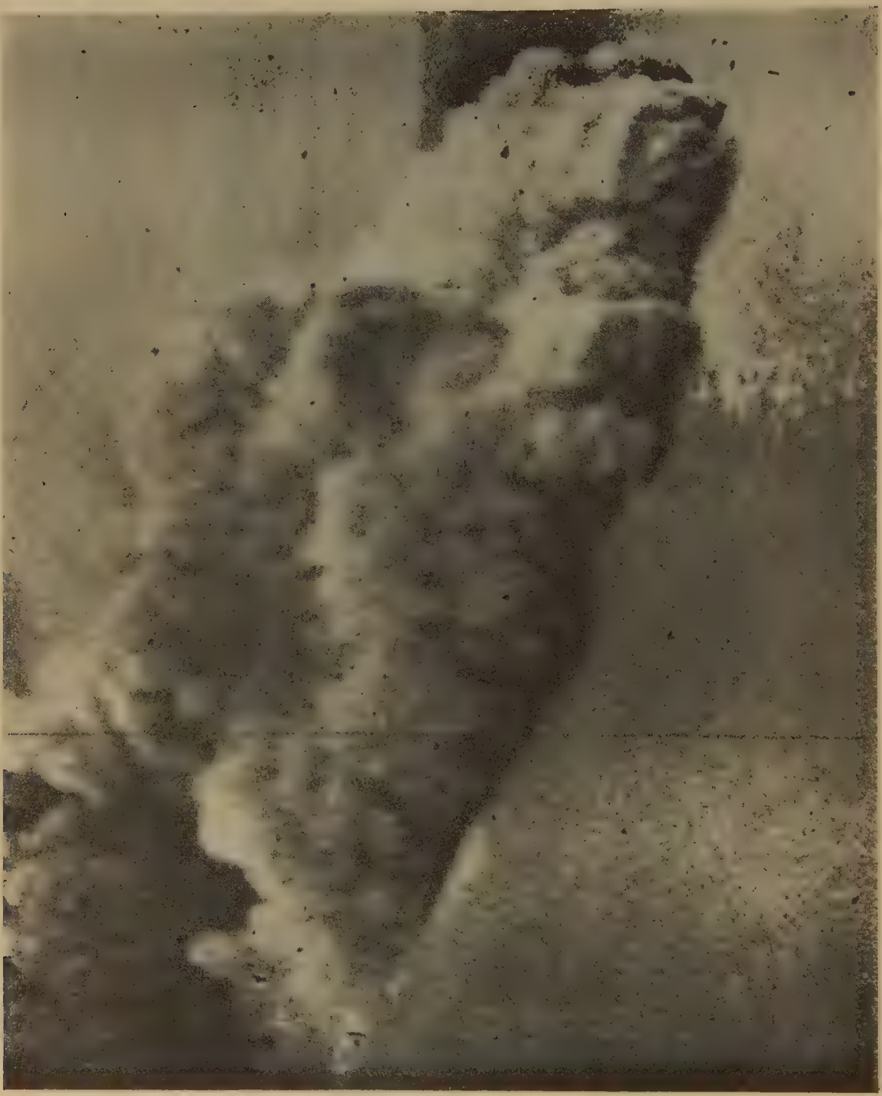
(R PETRIE photo)



Birth of Volcán Bárcena.

About 0805.

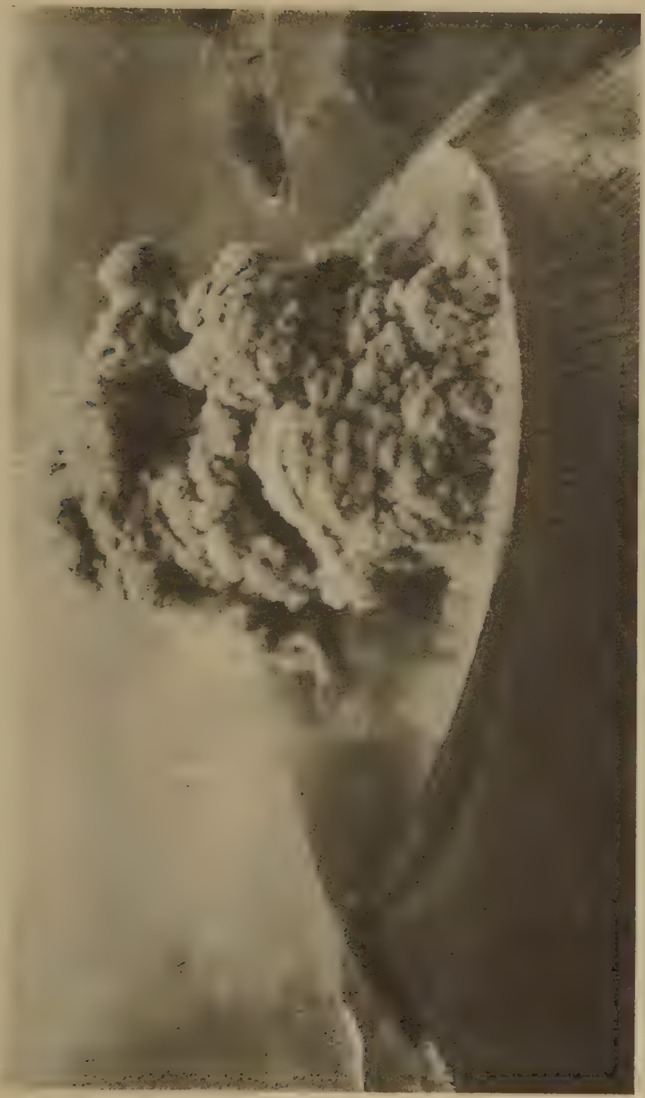
(R. Petrie photo)



August, 1952, eruption of Bárcena.

Volcanic density flow (tephra avalanche) of August 12, on Bárcena cone. Crater rim upper left corner, south side of Cráter Herrera extreme right center. Unretouched enlargement from a 16 mm duplicate Kodachrome motion picture frame.

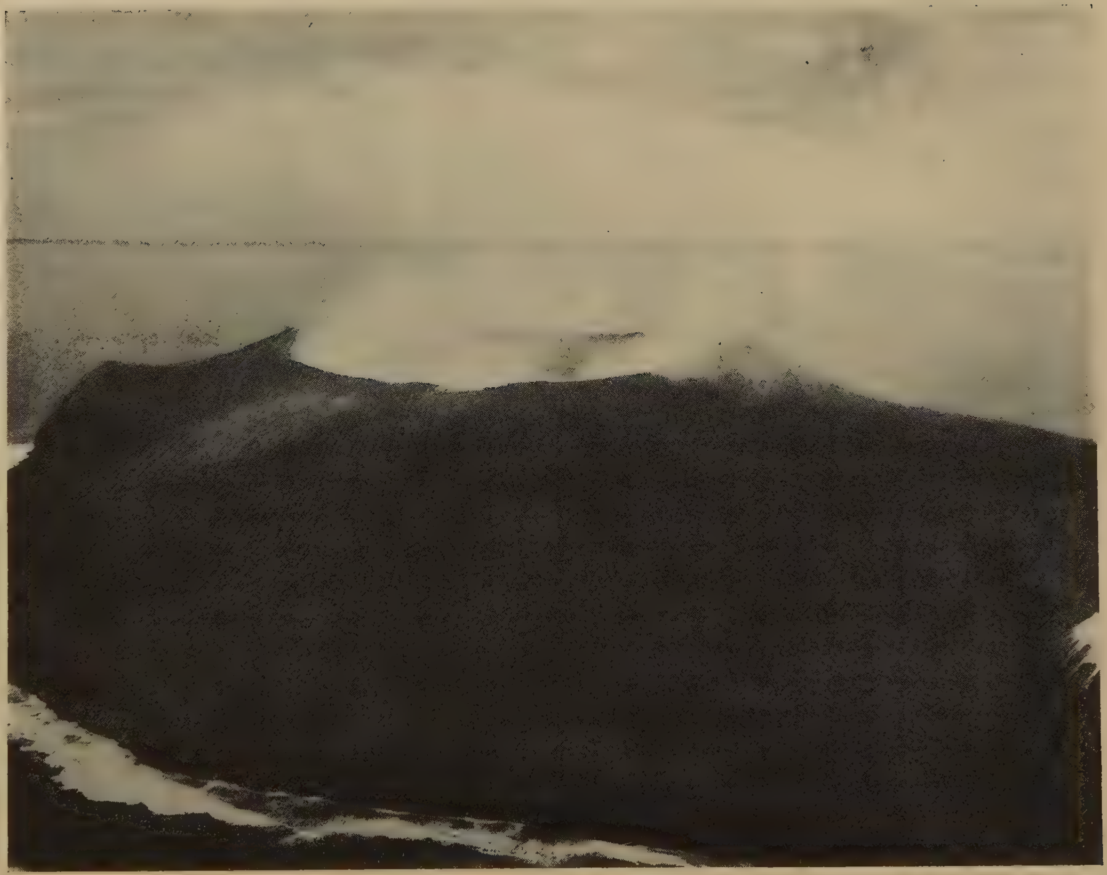
(T. HOWELL photo)



(U. S. Navy photo)

Bárcena in eruption September 12, 1952.

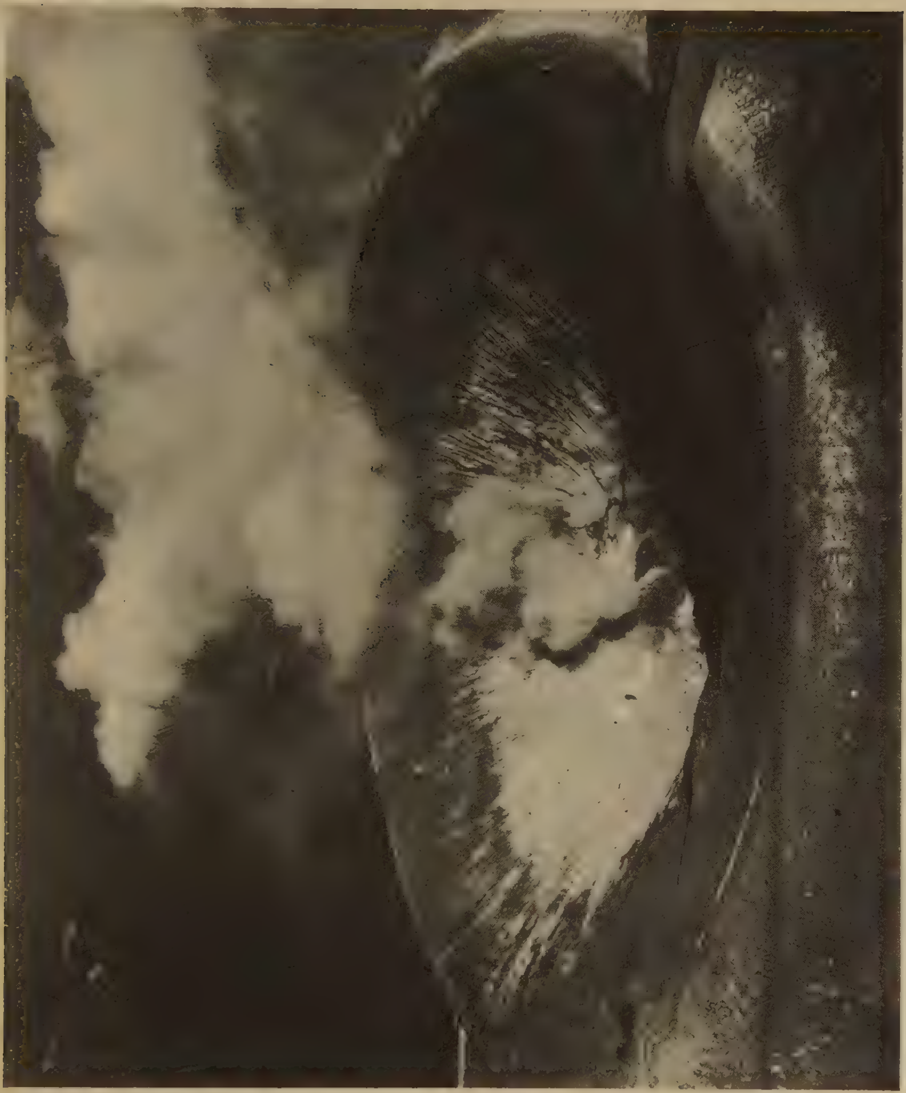
Weak vulcanian-type eruption.



Bárcena in eruption September 12, 1952.

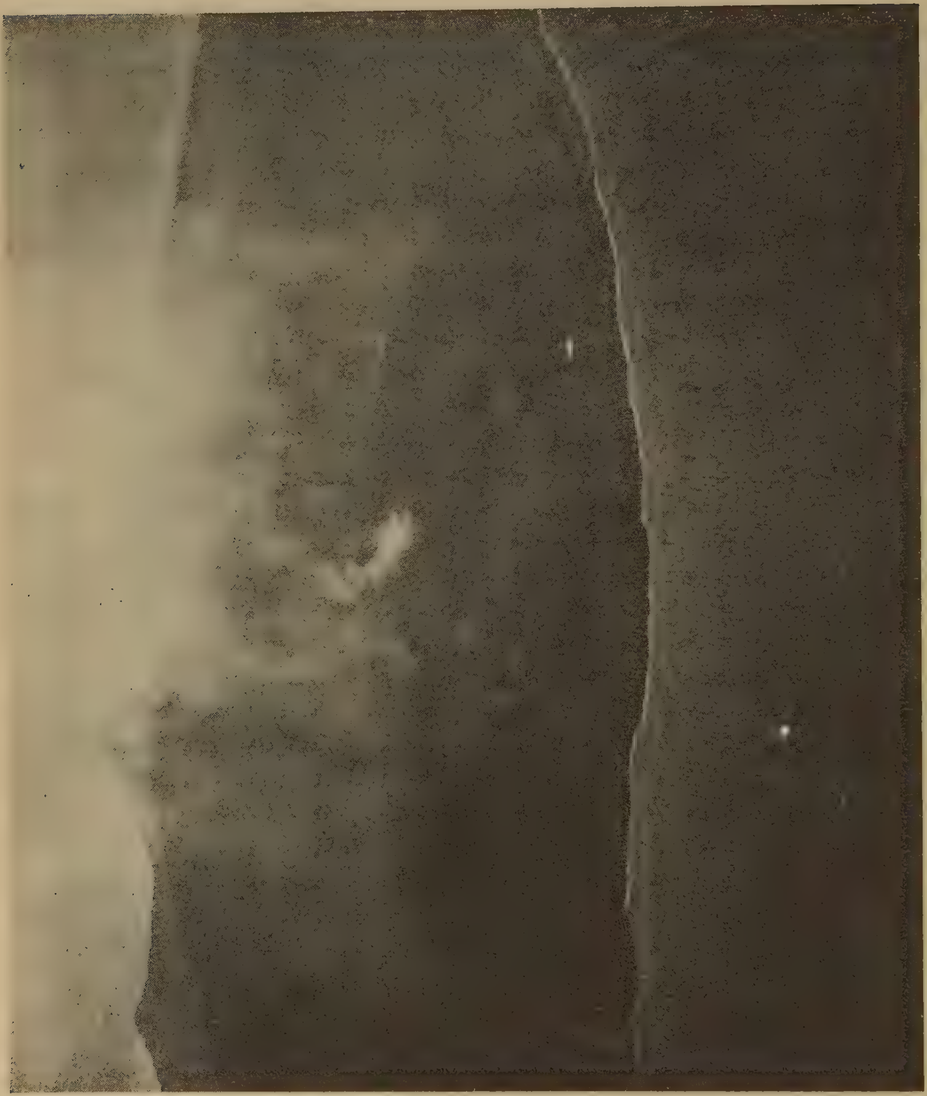
Furrows on east flank. Cráter Herrera extreme right.

(U. S. Navy photo)



Bárcena crater dome.

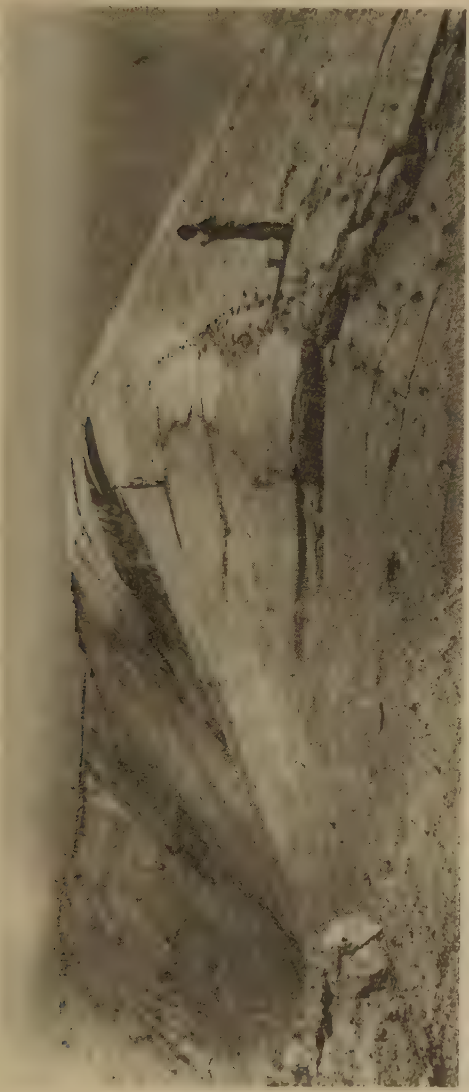
September 20, 1952. Steam issues from proto-dome. Wing of plane points to the terrace on the west side of the crater.
(U. S. Navy photo)



Bárcena crater dome.

November 15, 1952. Viscous trachyte lava half-fills the crater. Montículo Cinerítico in left background.

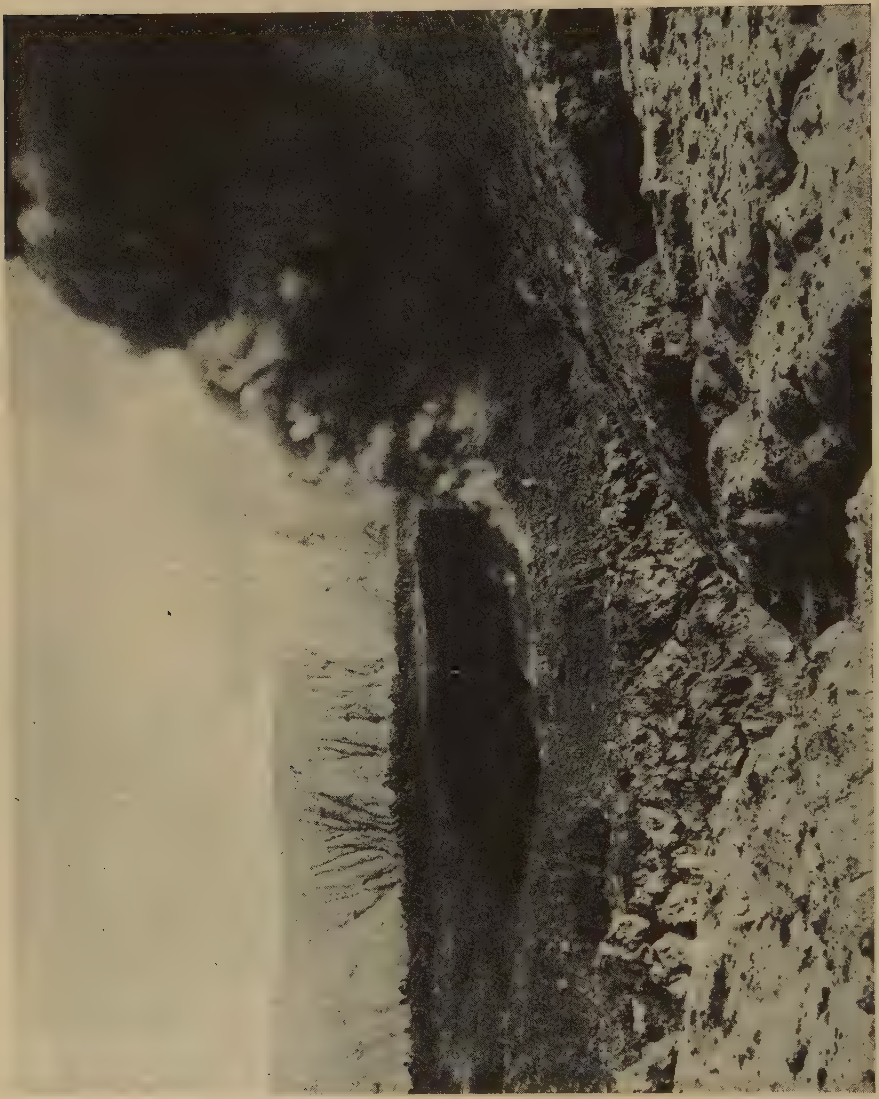
(U. S. Navy photo)



Rim of Bárcena crater.

South or leeward side. Note the graben in the rim, top slightly left of center. December 10, 1952.
(L. W. WALKER photo)

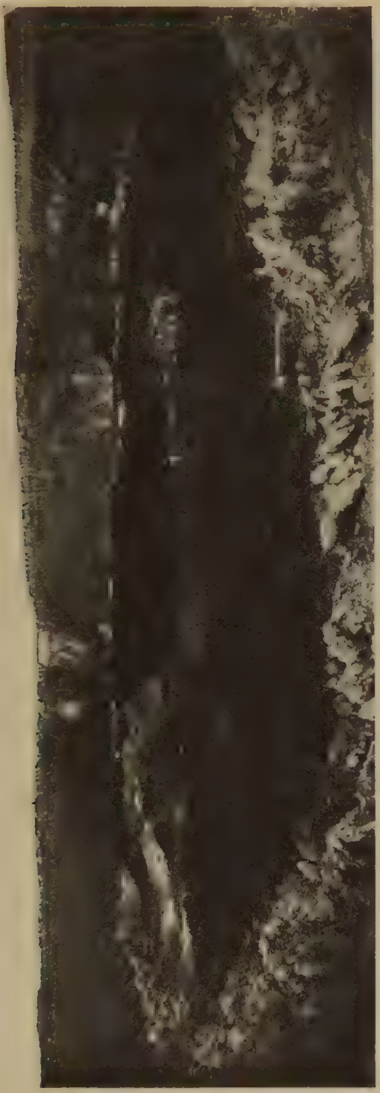
Pl. XII



Bárcena crater.

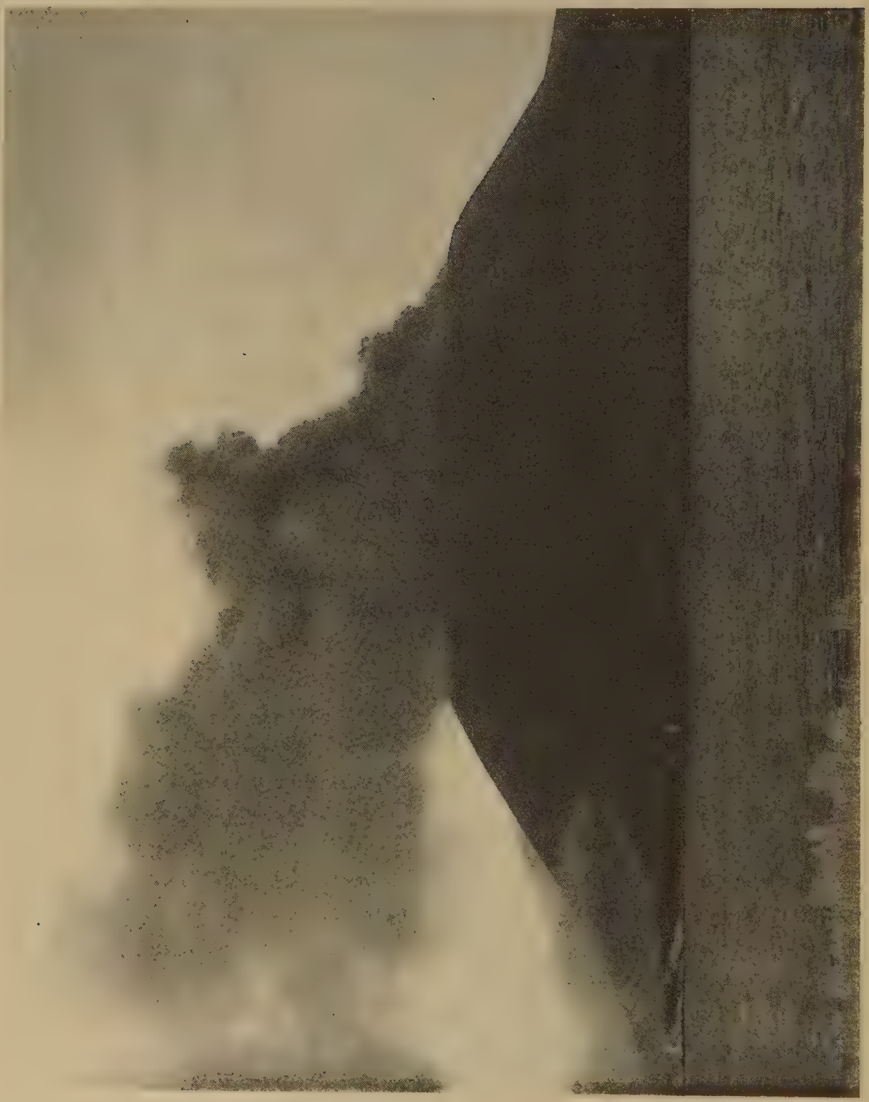
Steam eruption from the annular depression or « moat » between the inner and outer domes. December 10, 1952.

(L. W. Walker photo)



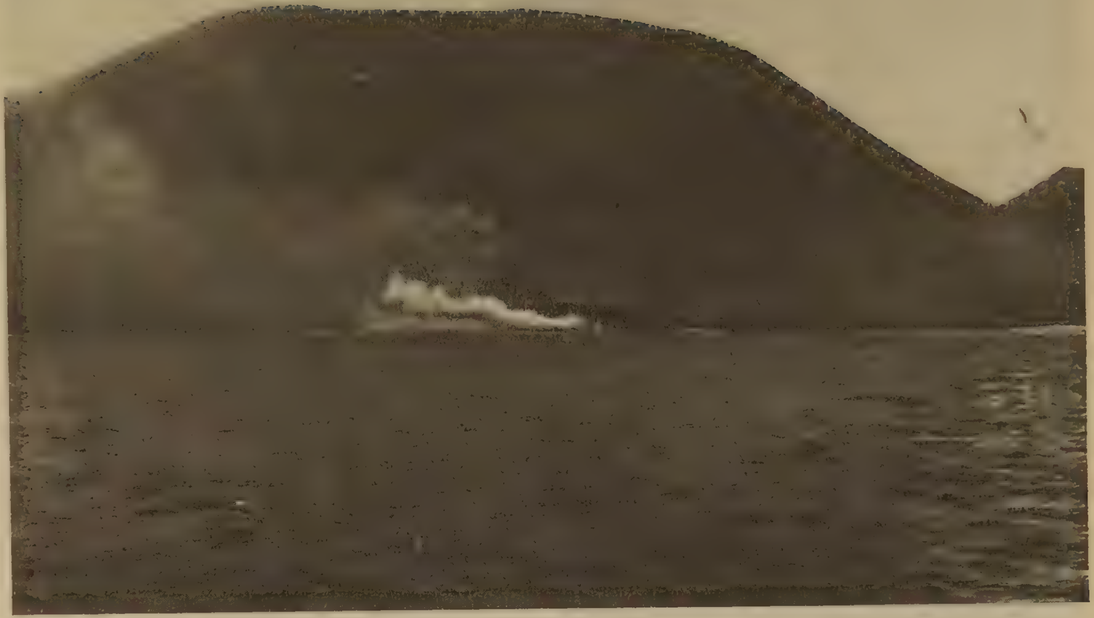
Bárcena crater in November, 1953. The crater wall is about 200 feet high above the dome. Raised edge of the dome in the foreground is about 40 feet high.

(A. F. Richards photo)



Eruption of Bárcena from the sea.

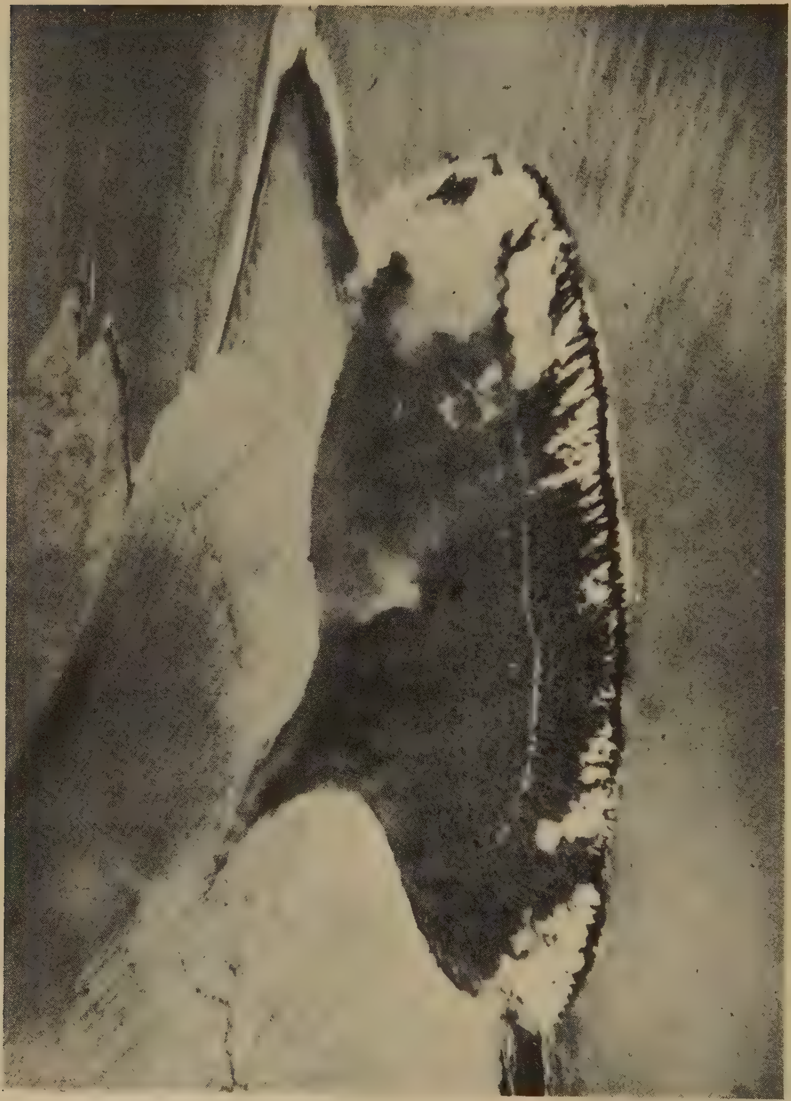
Eruption of December 12, 1952, photographed from the M/V *Southern Queen.* Delta Lávico at lower left.
(L. W. Walker photo)



Eruption of Bárcena from the sea.

Delta Lávico and Volcán Bárcena on December 9 from the yacht *Observer*. Steam from the seaward margin of the flow, darker gas from the vent. Note graben in the crater rim.

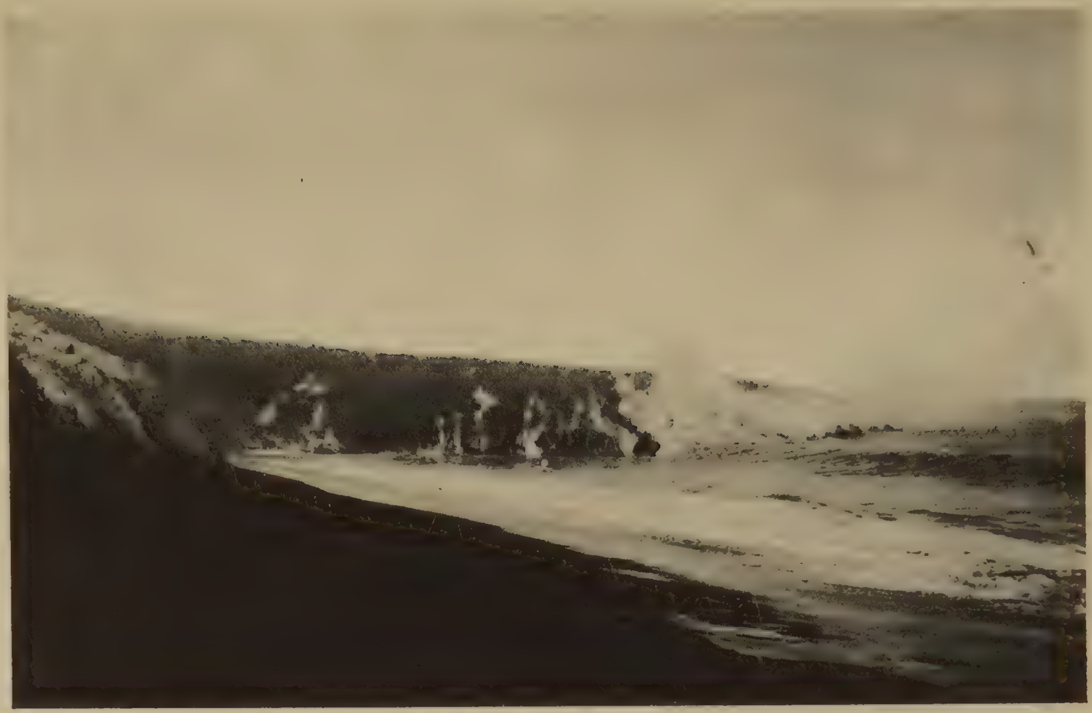
(L. W. Walker photo)



Delta Lávico.

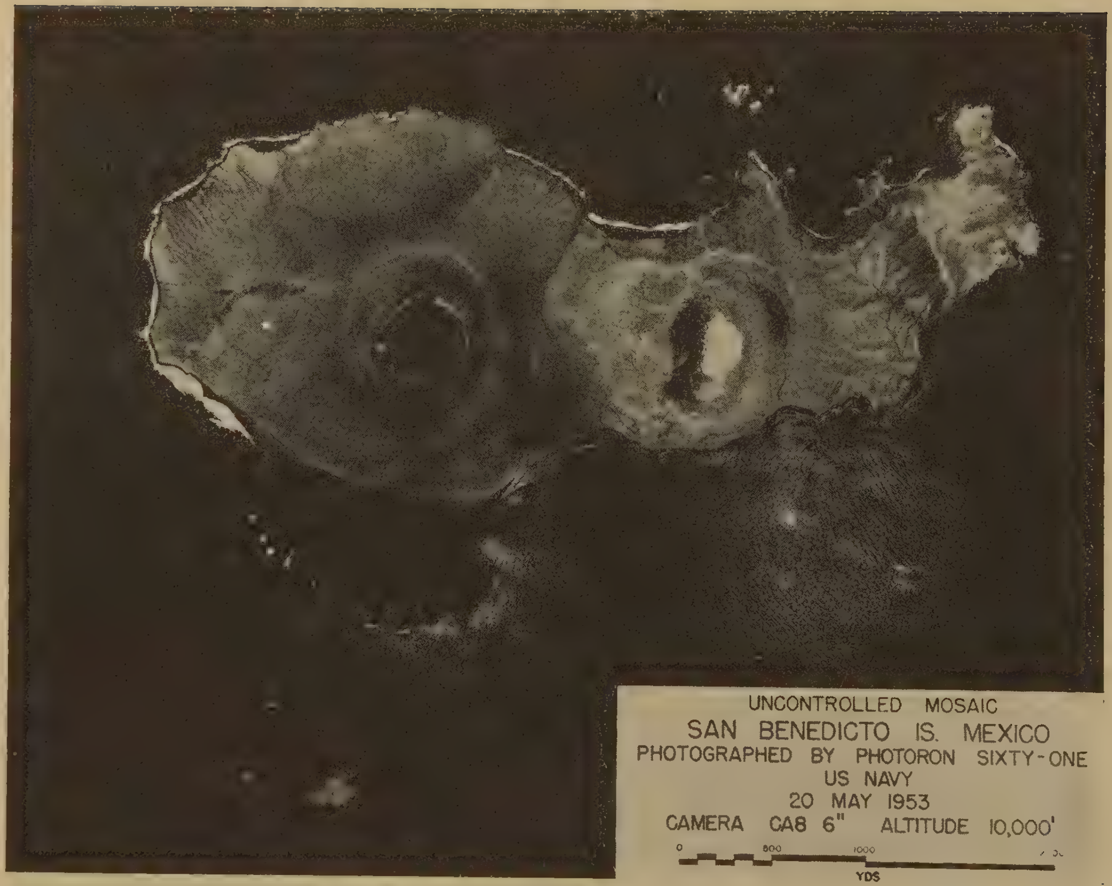
Delta Lávico from the air on December 11, 1952. View looking north. Seaward extent of flow 900 feet, width about 1100 feet.

(A. F. RICHARDS photo)



Delta Lávico.

Profile of flow from Volteadura Beach on December 11. Seaward slope of flow about 14°.
(L. W. Walker photo)


UNCONTROLLED MOSAIC
SAN BENEDICTO IS. MEXICO
PHOTOGRAPHED BY PHOTORON SIXTY-ONE
US NAVY
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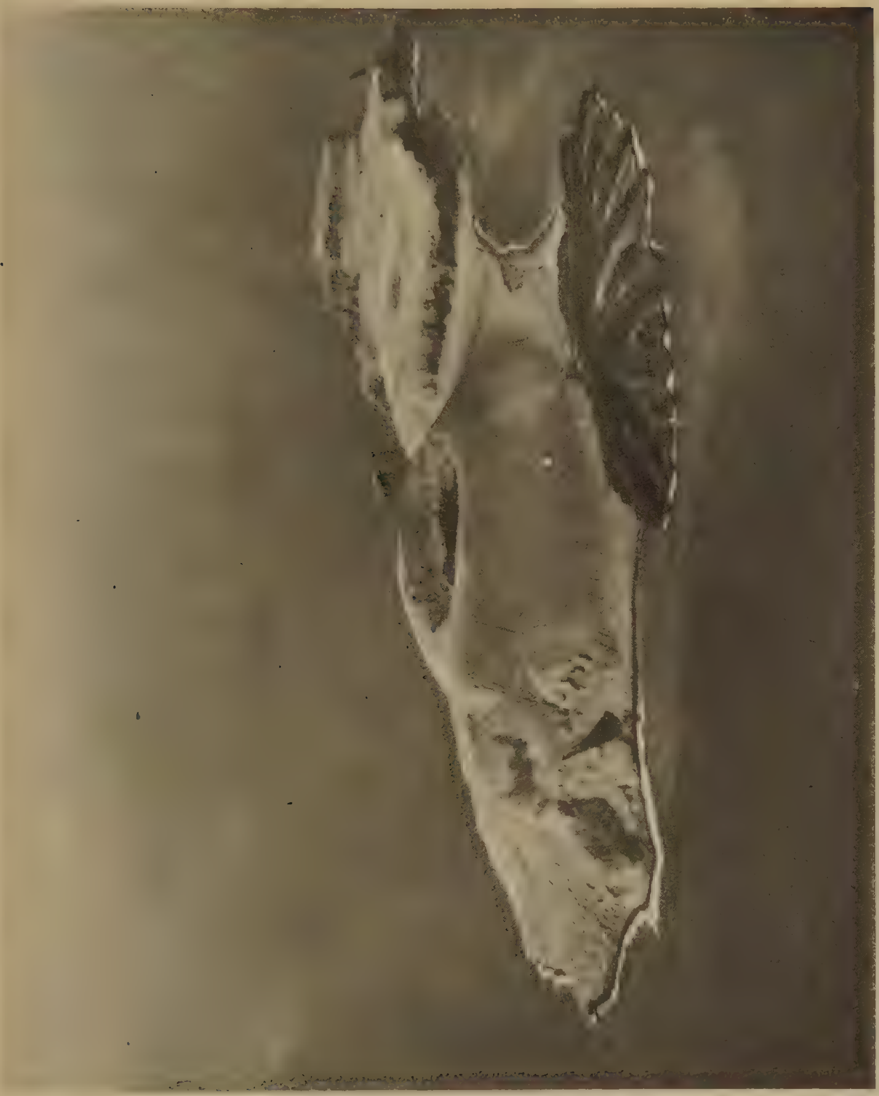
Isla San Benedicto from the air.

Mosaic of island before erosion of the Delta Lávico. Dark areas on the delta represent the last flows of lava. Note the two solfatara craterlets in Bárcena crater. The white area in Cráter Herrera is a playa deposit of very fine-grained tephra washed from the walls of the crater, which is a basin of internal drainage.

(U. S. Navy mosaic)

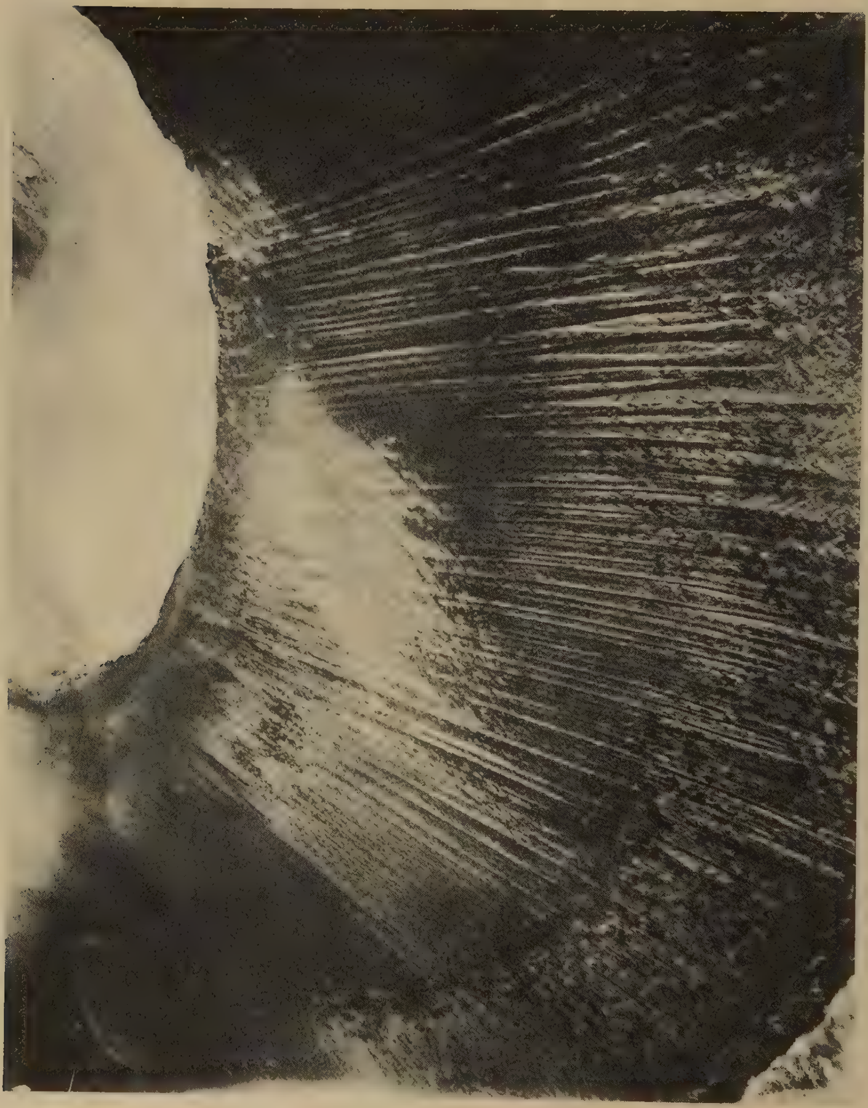


Isla San Benedicto from the air.

Oblique air photograph taken in March, 1955. Montículo Cinerítico to left of Bárcena, Cráter Herrera to right. Note that wave erosion has truncated the ends of the flow tongues and has tended to fill the indentations between tongues.

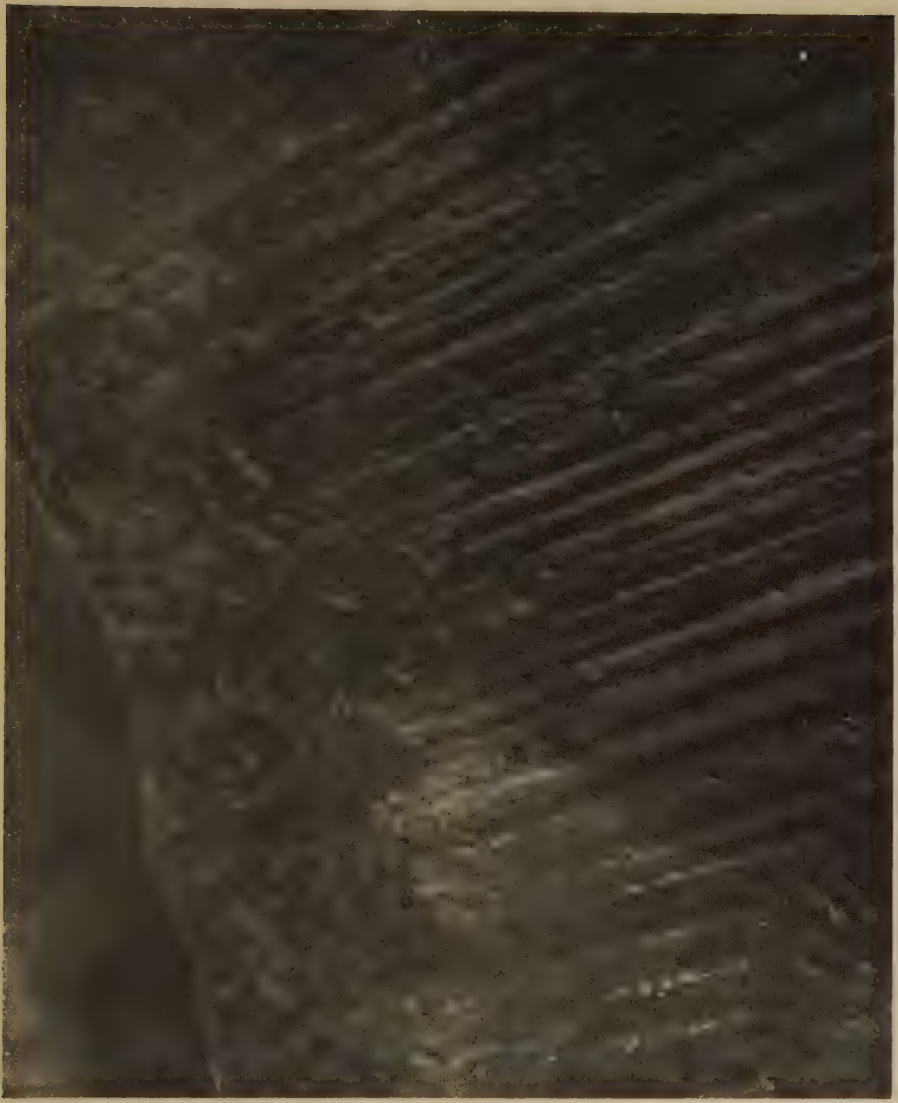
(A. F. Richards photo)

Pl. XX



Furrows on the east flank of Bárcena, September 12, 1952. The sea cliff and ocean are shown in the lower left corner. The light-colored areas represent recent deposits of ash. Photographs in Plates XXI and XXII are taken to the right of the largest fresh deposit of ash.

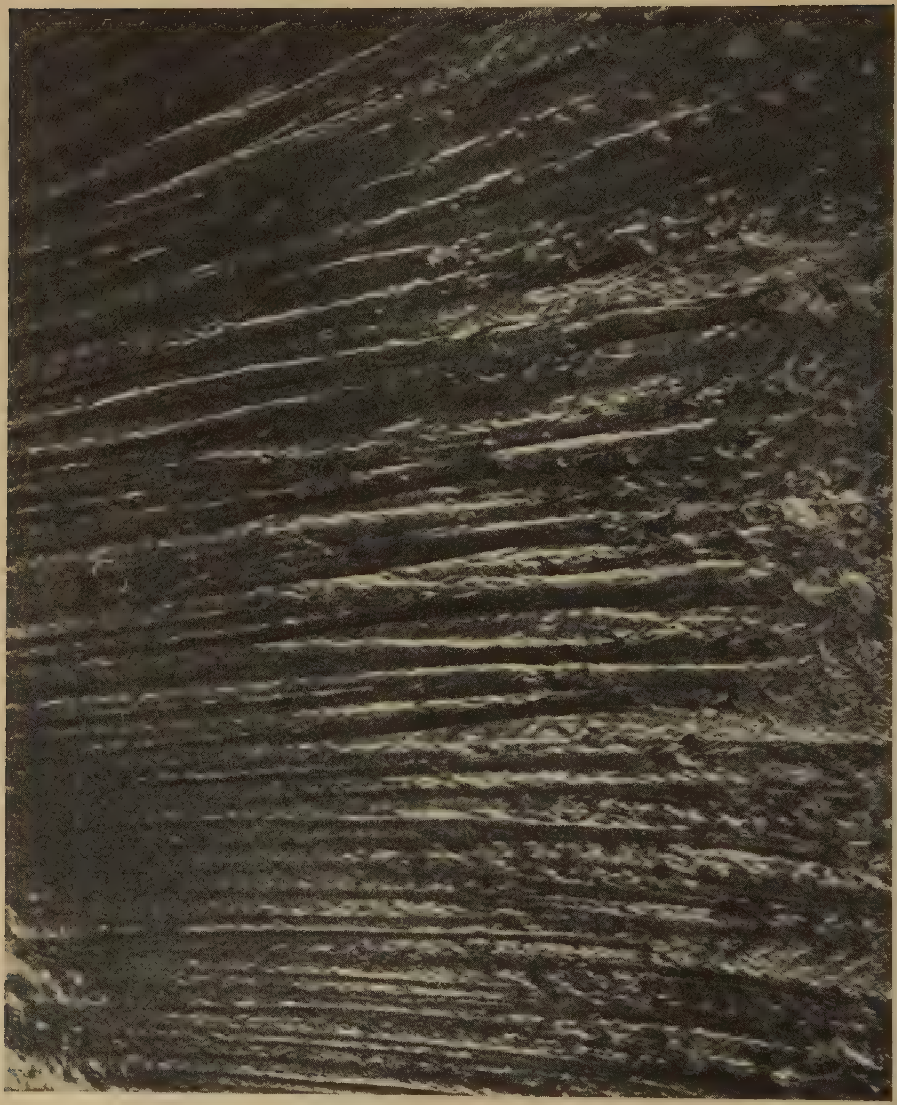
(U. S. Navy photo)



Furrow detail on the east flank of Bárcena.

Upper ends of the furrows.

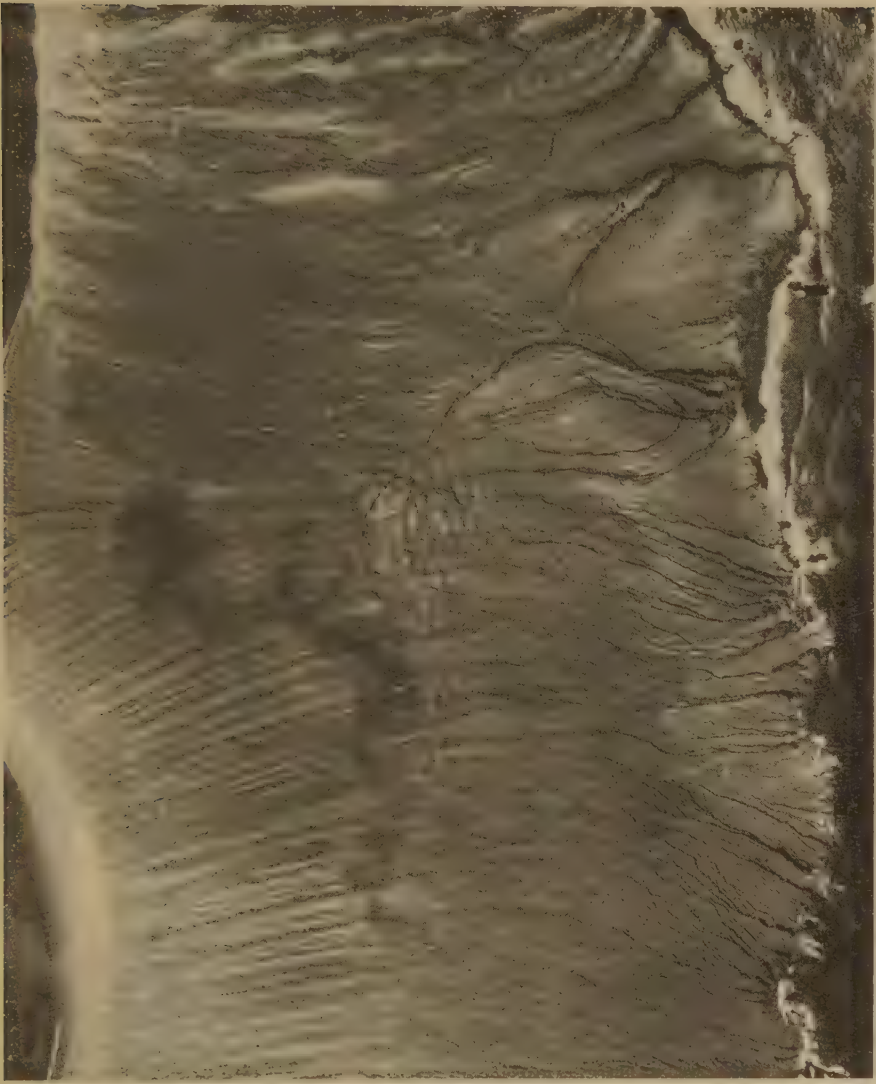
(U. S. Navy photo)



Furrow detail on the east flank of Bárcena.

Lower end of the furrows almost directly below Plate XXI.

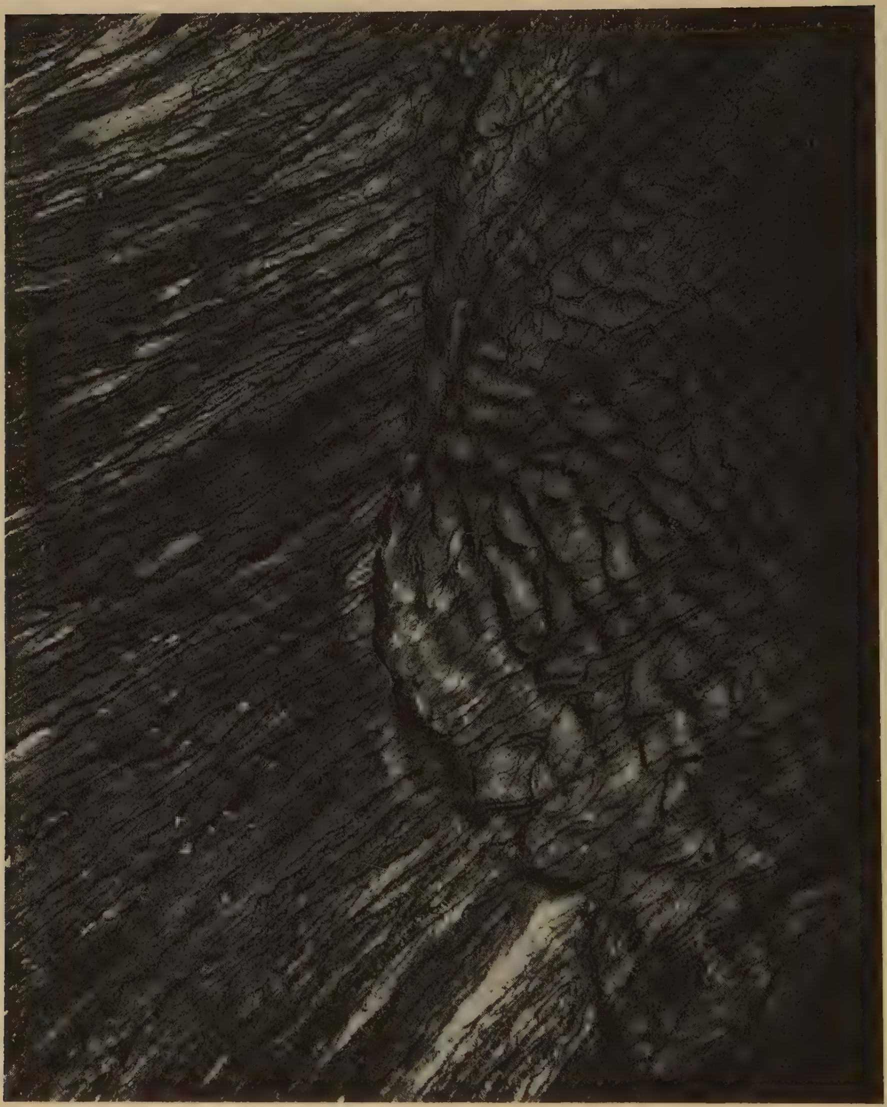
(U. S. Navy photo)



Furrows on the west flank of Bárcena, September 20, 1952.

General view. Crater rim in upper left corner. Note absence of straight-type furrows on Montículo Cinerítico (to right). The furrows on Bárcena (to left) have been modified by rains subsequent to their formation.

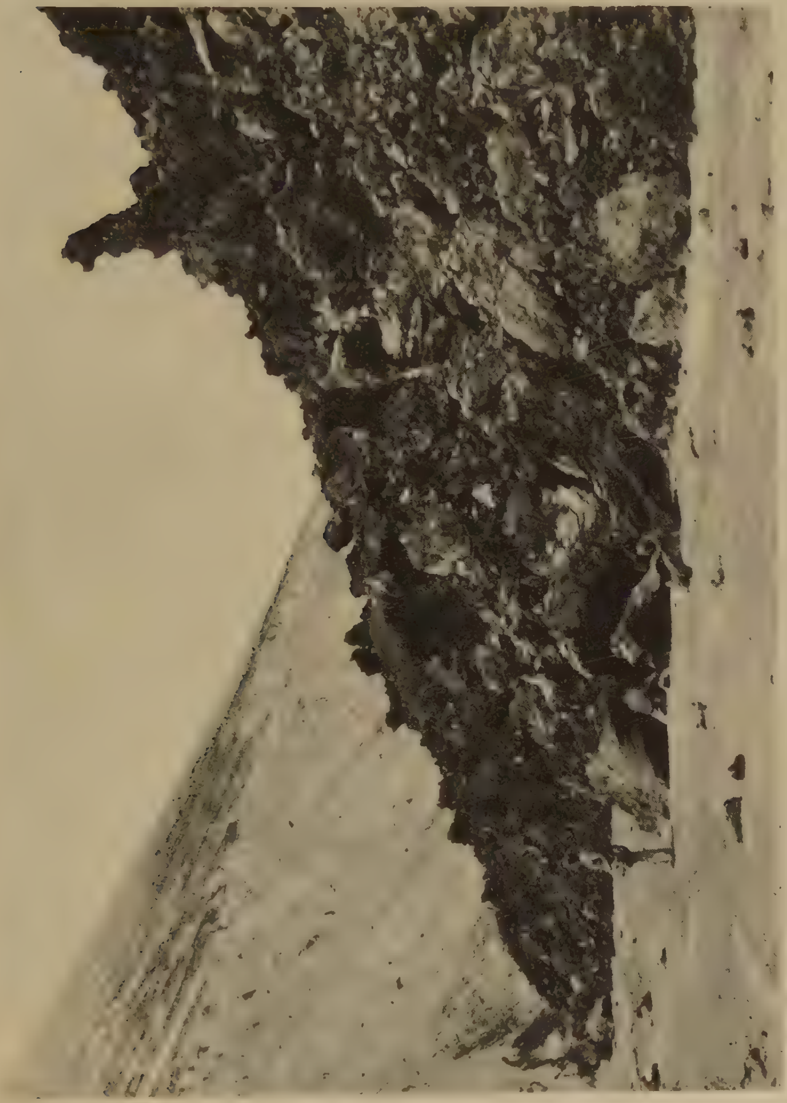
(U. S. Navy photo)



Furrows on the west flank of Bárcena, September 20, 1952.

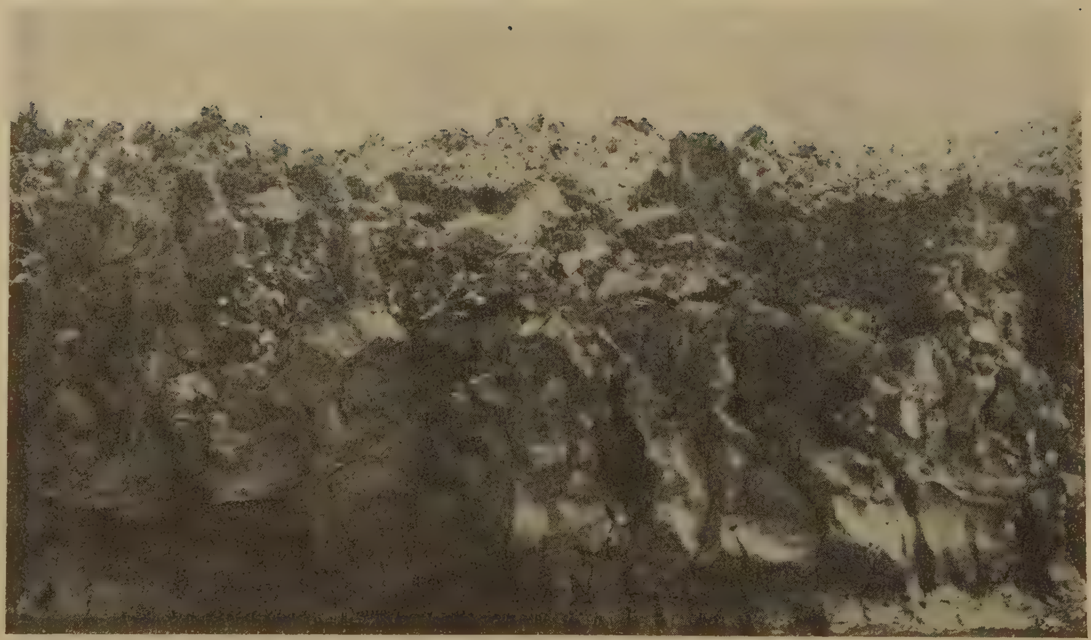
Close-up of the peculiar topography shown in the center of Plate XXIII. The pattern in the ash is believed to have been caused by tephra avalanches when they encountered the abrupt change of slope in this area. This pattern does not appear to be related to any pre-eruption buried topography.

(U. S. Navy photo)



Structure of the Delta Lávico, in May, 1955.

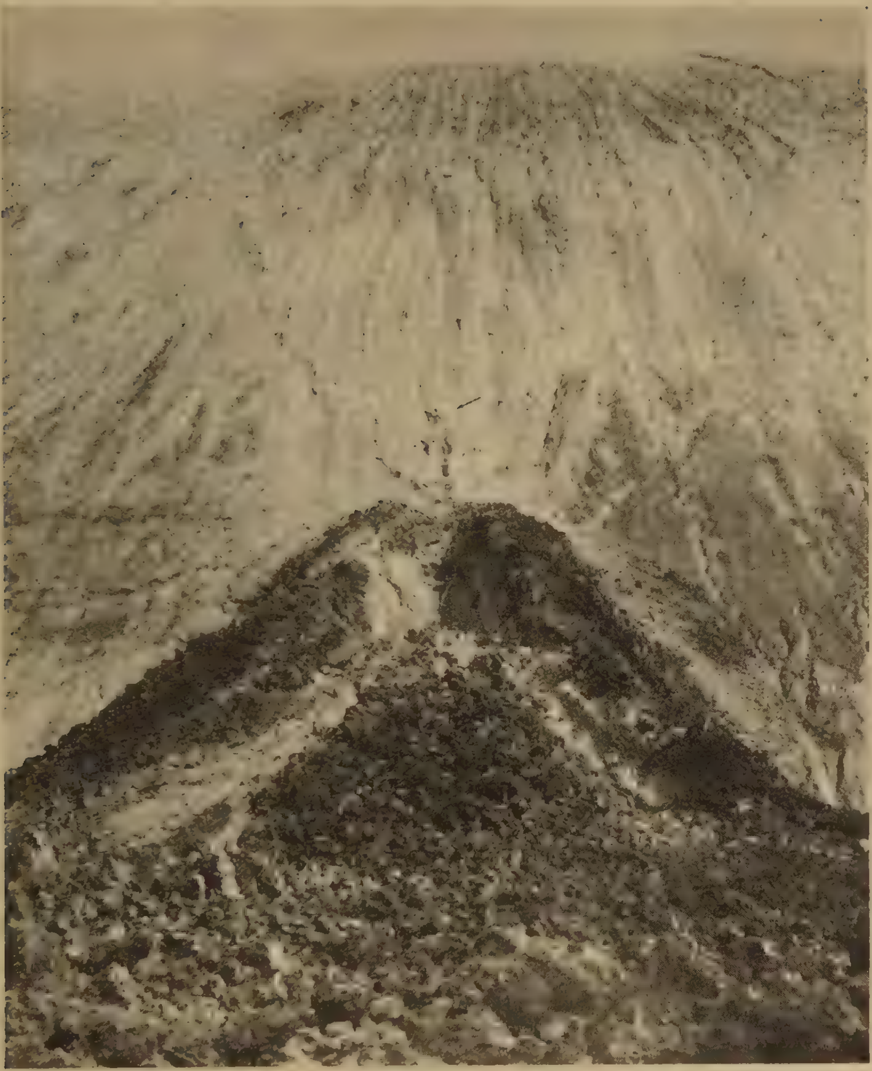
Side of the scoriaceous block lava flow facing Volteadura Beach. Note the conchoidal fracture of the larger blocks.
(R. Gilmore photo)



Structure of the Delta Lávico, in May, 1955.

Cross-section of a flow tongue which has been truncated by wave erosion. Scoriaceous clinker on the top grades to massive lava in the flow interior, which shows columnar jointing. Diagonal line to the left is part of the rigging of the R/V *Crest.*

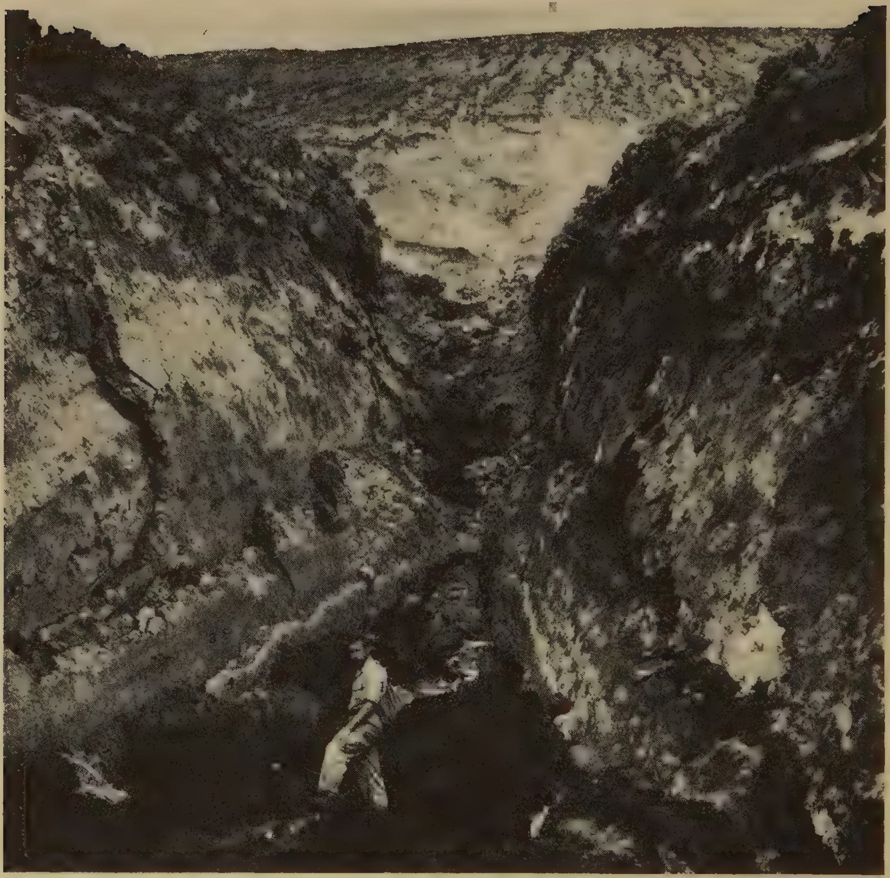
(R. Gilmore photo)



Delta Lávico vent in November, 1953.

General view from the top of the delta. Solfatara depression in the side of the cone above the vent is indicated by an arrow.

(A. F. Richards photo)



Delta Lávico vent in November, 1953.

Mouth of the vent. Four stages of the flow are labeled on the side of the vent to the left. The light-colored area above the vent is the solfatara depression.

(A. F. Richards photo)

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Sedimentation on the Ocean Floor

GUSTAF O. S. ARRHENIUS
Scripps Institution of Oceanography

Minerals accumulating on the ocean floor from suspension or solution in sea water have their origin in all the geospheres and in outer space. Owing to differences in physicochemical processes involved in the formation of solids in the lithosphere, the hydrosphere, the biosphere, the atmosphere, and extraterrestrial space, the source of sedimentary minerals can often be determined from their isotopic or elemental composition, crystal structure, or other characteristic properties. Variations in the rate and type of contribution from these different sources can be traced in the sedimentary record, and they yield information on the geological history of the earth. Events that have a global or wide regional effect and a duration in time of the order of 10^3 years or more are particularly well registered in the pelagic deposits, and in favorable cases can be quantitatively reconstructed.

Lithogenous Components

The lithogenous components of pelagic sediments are chemically unaltered debris of igneous and metamorphic rocks, mechanically disintegrated by weathering, transport processes, or volcanic eruptions, and transported into the ocean by wind or water. Some of the components of igneous and metamorphic rocks are unstable in sea water and transform rapidly into stable hydrous minerals, especially when present in a finely divided state. Quartz, feldspar, and mica are the most common relatively stable lithogenous minerals found in ocean sediments.

The rate of lateral transport by ocean currents is low in comparison with the sinking rate in water of sand- and silt-sized mineral grains, and of the flocs formed by coagulation of the fine-grained fraction of silicate minerals. As a result, the bulk of water-borne detrital mat-

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ter from continents and islands is deposited in a zone with a width of a few hundred kilometers or less, surrounding the source areas. The rate of accumulation in areas of continuous deposition within this zone varies between the order of 10^{-1} cm·millennium^{-1} in the peripheral part and several orders of magnitude higher in the inner part. Thus, continents, islands, and seamounts are surrounded by sedimentary and volcanic aprons, ending in smooth plains, which border the low-relief areas typical of very low rates of deposition (Menard, 1956) (fig. 1).

Owing to submarine slumping, solifluction, and discharge of rivers with a high sediment load into the ocean, high-density suspensions are generated, which can be propagated along the ocean bottom over long distances (Kuenen and Migliorini, 1950). The marginal zone of rapid deposition around continents and islands is broadened by these processes, especially where, as in the Atlantic Ocean, the submarine channels perpendicular to the coast feed the suspension beyond the continental shelf into the deep ocean. Troughs and ridges parallel to the coast, as in parts of the Indo-Pacific Ocean, impede the spreading of sediments by turbidity flow into the ocean basins.

The lowest rates of contribution of lithogenous and other continental minerals accordingly are found in ocean basins far from land and protected against turbidity flow by trenches and ridges. Examples of such areas are shown in figures 1 and 2. The contribution of lithogenous minerals to sedimentation in such protected areas appears to be of the order 10^{-2} to 10^{-1} cm·millennium^{-1} and to consist mainly of windborne material. The rate of supply of this material consequently reflects the distribution over the earth of arid source areas and of strong, persistent air currents. This is exemplified by the occurrence of atmospheric dust around the continents (fig. 3) and by the high quartz content of Pacific sediments below the tropical jet stream in the northern hemisphere (Goldberg and Rex, 1958).

Hydrogenous Components

Hydrogenous minerals are formed from solutes in the ocean or in the continental part of the hydrosphere. It has been demonstrated (Correns and von Engelhardt, 1938) that the components of igneous silicates are ionically dissolved in weathering, and hydrogenous minerals like the clays appear to be formed largely by precipitation from such solutions. It is not known to what extent the clay minerals of pelagic deposits are precipitated from solution in the ocean, or to what

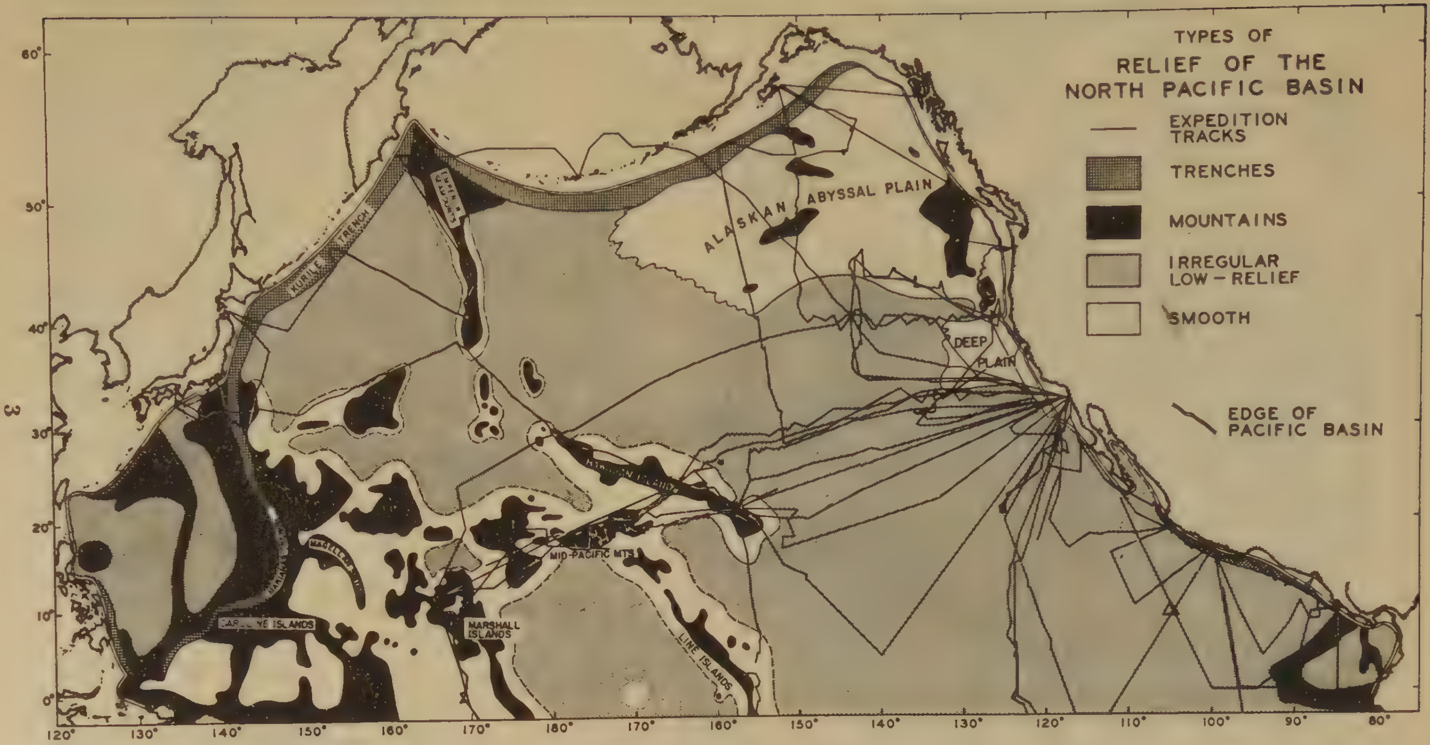
TYPES OF
RELIEF OF THE
NORTH PACIFIC BASIN
EXPEDITION TRACKS
TRENCHES
MOUNTAINS
IRREGULAR LOW-RELIEF
SMOOTH
EDGE OF PACIFIC BASIN
ALASKAN ABYSSAL PLAIN
DEEP PLAIN
KURILE TRENCH
EMPEROR SEAMOUNTS
HAWAIIAN ISLANDS
MID-PACIFIC MTS
MARSHALL ISLANDS
LINE ISLANDS
CAROLINE ISLANDS
MARIANAS
MAGELLAN MTS
60°
50°
40°
30°
20°
10°
0°
120°
130°
140°
150°
160°
170°
180°
170°
160°
150°
140°
130°
120°
110°
100°
90°
80°

Fig. 1. Types of relief of the North Pacific Basin (from Menard, 1958, by permission).

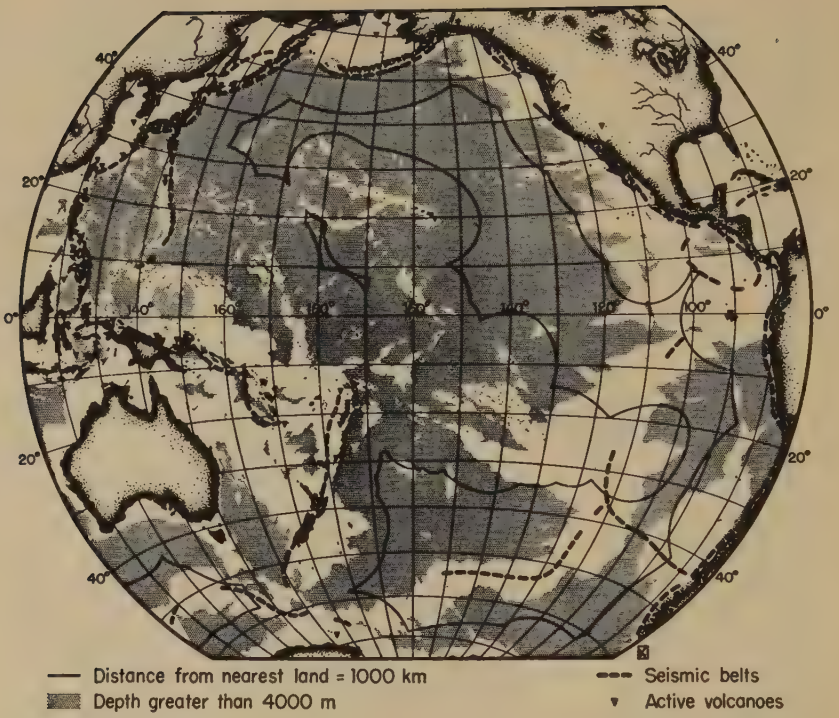
40°
20°
0°
20°
40°
140°
160°
180°
160°
140°
120°
100°
40°
20°
0°
20°
40°
— Distance from nearest land = 1000 km
▨ Depth greater than 4000 m
--- Seismic belts
▾ Active volcanoes

Fig. 2. Main topographic, seismic, and volcanic features of the Pacific (from Revelle, Bramlette, Arrhenius, and Goldberg, 1955, by permission).

proportion they represent precipitates formed shortly after dissolution of the continental igneous source minerals and subsequently transported into the ocean by water or wind (Arrhenius, 1954; Goldberg and Arrhenius, 1958). There is good evidence that montmorillonite is formed by decomposition of volcanic glass on the ocean floor. The problem of the site of formation of clay minerals is of interest from a general geochemical and petrological as well as from a historical-geological point of view, as variations in time of the composition of any clay minerals of marine origin would reflect variations in the composition of the ocean. Such a gradual change from Cambrian to Recent is indicated by the composition of the clays on the Siberian shield (Vinogradov and Ronov, 1956). Other workers, however, suggest that most of the clays are formed at the site of weathering and subsequently transported to the sea (Weaver, 1958). Evidence for a continental or marine origin of hydrous silicate minerals of the ocean

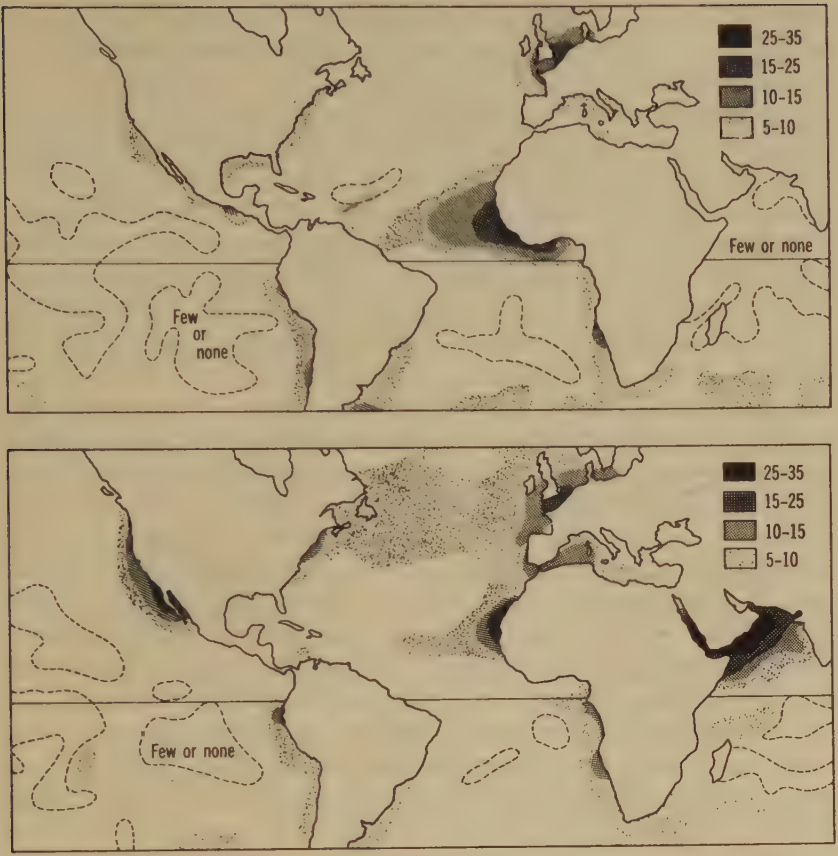

Fig. 3. Average frequency of haze during northern winter (upper graph) and summer season (lower graph). The figures indicate reported cases of haze in percentage of total number of observations. Haze is defined as generally due to microscopic particles in the atmosphere, such as smoke, dust, or salt, with visibility 1 to 2 km, as distinguished from mist and fog, caused by droplets of water.

The extensive transport of eolian sand and dust by the harmattan in winter and by the southwest monsoon in summer is indicated by the high corresponding frequencies of haze. This transport is also evident from the content of silt-sized rounded calcite and quartz, the quartz frequently with blistered surface and ferric hydroxide coating of the grains, in the sediments below the areas of high haze frequency in the equatorial Atlantic and Indian Ocean (Correns, 1953; Radczewski, 1939; Arrhenius, 1950). Similar evidence is found in the Mediterranean (Norin, 1958).

The haze area in northwestern Europe is probably due to industrial smoke production. Forest fires are believed to contribute to the Atlantic high-latitude haze during the northern summer. (Redrawn from McDonald, 1938.)

floor could be derived from their oxygen isotope composition and from studies of the distribution and turnover of dissolved species of aluminum in sea water.

A frequently occurring component of slowly depositing pelagic sediments is the zeolite phillipsite. The relatively large size of the crystals, and their occurrence, make it clear that this silicate mineral is definitely of marine hydrogenous origin, but little is known so far about its mode of formation. Owing to its high ion-exchange capacity phillipsite appears to play an important role in the sorption of ions diffusing through the sediment. As a result, variations in concentration of this zeolite markedly influence the ultimate distribution of radium in the sediment as described below.

Another hydrogenous component of importance in pelagic deposits is a group of hydrated manganese–iron oxide minerals that constitute microscopic aggregates distributed through the sediment. In places where the micronodules remain at the sediment surface for a considerable length of time, they grow to macroscopic dimensions, and finally cover parts of the ocean bottom as a pavement. Such pavements are estimated to extend over 10 per cent of the ocean floor (Menard, personal communication), and constitute high-grade manganese ores of potential usefulness (Goldberg and Picciotto, 1955; Dietz, 1955). The rate of growth appears to vary between the order of 10^{-2} and 10^{-3} $\mathrm{cm \cdot millennium^{-1}}$. The crystal structure is strongly disordered and has recently been demonstrated (Buser and Grütter, 1956) to be a double layer consisting of MnO_2 alternating with $Mn(OH)_2$ together with $Fe(OH)_3$ and varying amounts of other heavy metals like Pb, Mo, Co, Cu, Zn, Th, and the rare-earth elements. It has been suggested that the manganese nodules are formed by catalytic oxidation of the manganous ion in sea water by a gel film of ferric oxide hydrate, formed at the bottom surface by discharge of the ferric oxide hydrate colloid in sea water (Goldberg and Arrhenius, 1958). Heavy-metal ions are scavenged from sea water by this process, and by similar ones referred to below. Coprecipitation and sorption thus appear to be the most important mechanisms regulating the concentration of these ions in the ocean.

The solubility relations of apatite in sea water are not well known, although it is evident that apatite is unstable in present-day deep water which has a low temperature and a high CO_2 tension; the apatite of skeletal remains thus slowly goes into solution on the ocean floor. In shallow water, hydrogenous apatite appears to form today from phosphate ion in solution, largely by isomorphous replacement of calcite, which is also sometimes found to be altered into dolomite (Bramlette, personal communication). The widespread occurrence of hydrogenous apatite in the Lower and Middle Tertiary sediments, outcropping on seamounts and other topographic highs in the Pacific Ocean, suggests that the replacement process was operative over a greater depth range in pre-Pleistocene time, when the deep water had a temperature higher than the present one by 10° or more. Such a temperature differential is indicated by oxygen-isotope measurements on benthonic foraminifera (Emiliani and Edward, 1953).

Owing to its peculiar structure, biogenous apatite dissolving on the deep sea floor offers a suitable surface for the adsorption and fixation as phosphates of the rare-earth elements and of thorium isotopes (Arrhenius, Bramlette, and Picciotto, 1957). Rare-earth contents up to a few per cent of the aggregate weight are thus accumulated, and a large part of the thorium, including ionium (Th^{230}), is transferred from the sea water to the biogenous apatite. The apatite-bearing skeletal debris also contains an organic component consisting chiefly of alteration products of collagen. Heavy-metal ions, mainly Zn, Cu, Pb, Sn, and Ag, are transferred from sea water to these organic phases. The zinc concentration may amount to 5 per cent or more of the organic phase, and the element appears to occur as salts of higher fatty acids.

Marine hydrogenous barite is not common in most parts of the ocean, but in deposits below areas of high organic productivity it occurs in concentrations of several per cent, more than twenty times above the level found in adjacent areas (fig. 4). The barite occurs as euhedral

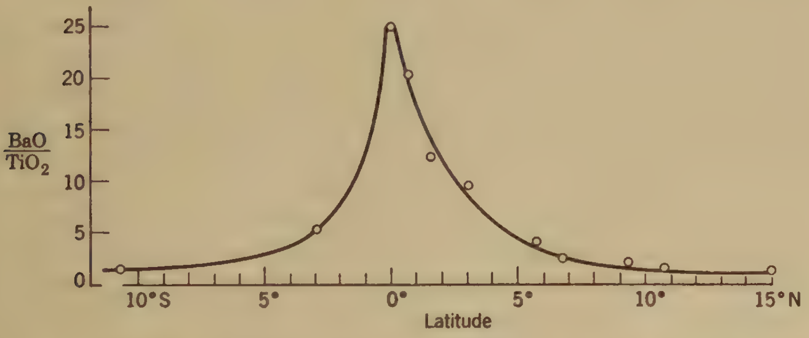

Fig. 4. Relative rate of accumulation of barium as a function of latitude, across the equatorial zone of high organic productivity. The rate is represented by the ratio BaO/TiO_2 in Postglacial sediments. (Redrawn from Goldberg and Arrhenius, 1958.)

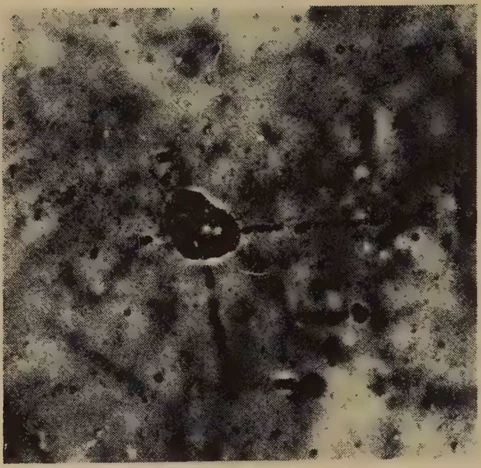

Fig. 5. Radioautograph showing α tracks emerging from fecal pellet with inclusions of barite. Track length, approximately 20 microns. The pellet is immersed in the nuclear photographic emulsion (from Picciotto and Arrhenius, unpublished).

crystals, mostly 3 to 20 microns in size, free or growing as inclusions in fecal pellets from mud-eating animals (fig. 5). The high rate of accumulation of barite in high-productivity areas and especially inside fecal pellets is believed to depend on an increased sulfate-ion concentration due to the decomposition of proteins and the subsequent oxidation of sulfide to sulfate ion by dissolved oxygen.

Biogenous Components

Skeletal remains of plants and animals form a large part of ocean sediments. Most abundant are remains of unicellular planktonic organisms with skeletal structures consisting of calcite or opaline silica. These, as well as other biogenous solids, are unstable under the conditions prevailing at the sediment-water interface in the deep ocean, with the order of decreasing solubility: aragonite, calcite, opal, apatite. The rates of accumulation of these components thus vary between wide limits: calcite, for example, from zero to the order of 5 $\text{cm} \cdot \text{millennium}^{-1}$. Calcite does not accumulate in areas where the dissolution rate outweighs the production rate, as at great ocean depths or below areas with moderate or low productivity of plankton having carbonate skeletons.

The highest rates of accumulation of calcite are found in tropical areas with high organic productivity in the surface layer of the ocean, as below the zone of upwelling along the equator in the East Pacific Ocean. In this zone diatoms form an important part of the phytoplankton, but the rate of accumulation of diatomaceous silica on the bottom reaches values only about one-fifth that of calcium carbonate. In the temperate and polar areas of high organic productivity, planktonic organisms with calcareous skeletons resistant enough to withstand dissolution are relatively rare, and diatomaceous silica is the most important biogenous component accumulating on the ocean floor.

Phosphatic debris of scales, bones, and teeth of fish forms a geochemically important component of ocean sediments, responsible for all the phosphorus now depositing on the deep ocean floor. The structure is typical of phosphatic skeletons in higher animals: a fibrous aggregate consisting of parallel-aligned apatite crystallites, elongated along the *Z* axis and with an interstitial matrix of alteration products of original collagen. The size of the apatite crystallites varies in different groups of organisms; average lengths of 300 to 400 Å were found in bone fragments of bathypelagic fish and 600 to 1200 Å in ear bones of whales, one of the few mammal remains found on the ocean floor. The internal surface of the apatite of fish debris, computed from the crystallite size, amounts to 100–200 $m^2 \cdot g^{-1}$, which partly explains the efficiency of the fish debris in scavenging heavy metals from sea water.

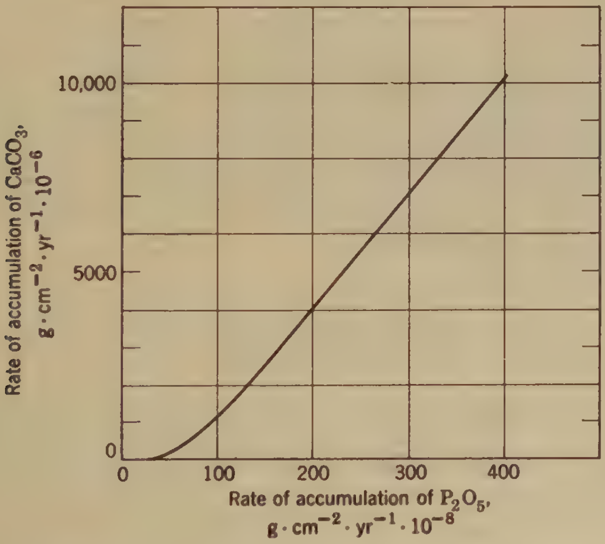

Fig. 6. Average relation between the rates of accumulation of calcium carbonate and of phosphate in sediments from the east equatorial Pacific (from Arrhenius, 1952, by permission).

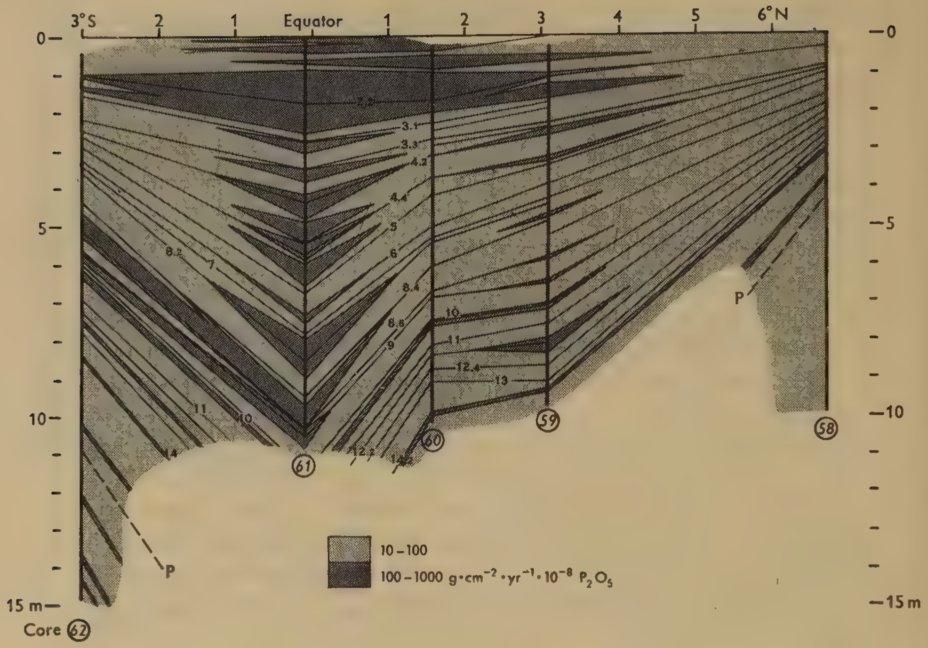

Fig. 7. Rate of accumulation of phosphate in a meridional section through the sediments of the east equatorial Pacific at about longitude 130° W. Vertical lines mark the sampling locations. The numbers in the figure indicate stratigraphic units. The highest rate of accumulation of phosphate is found below the equatorial zone of high productivity, and in the even-number stages and substages, which also show the highest rates of accumulation of biogenous calcite and opal. These units are interpreted as corresponding to ages and subages of an increased trade-wind intensity, and therefore of intensified upwelling and organic productivity in the equatorial divergence (from Arrhenius, 1952, by permission).

The concentration of fish debris is generally low and of the order of 0.1 to 5 per cent. The higher values in this range are found mostly in clay sediments laid down during Tertiary time, when the rate of transport of detrital material from the continents into the ocean was lower than in the Pleistocene, and consequently marine hydrogenous and biogenous components were less diluted by detrital minerals.

The rate of accumulation of fish debris is highly variable, and closely proportional to the rate of accumulation of calcium carbonate (figs. 6, 7, and 8). The rate of accumulation of biogenous apatite is another parameter reflecting organic productivity in the ocean, and the populations of fish responsible for the main part of the debris are stationary

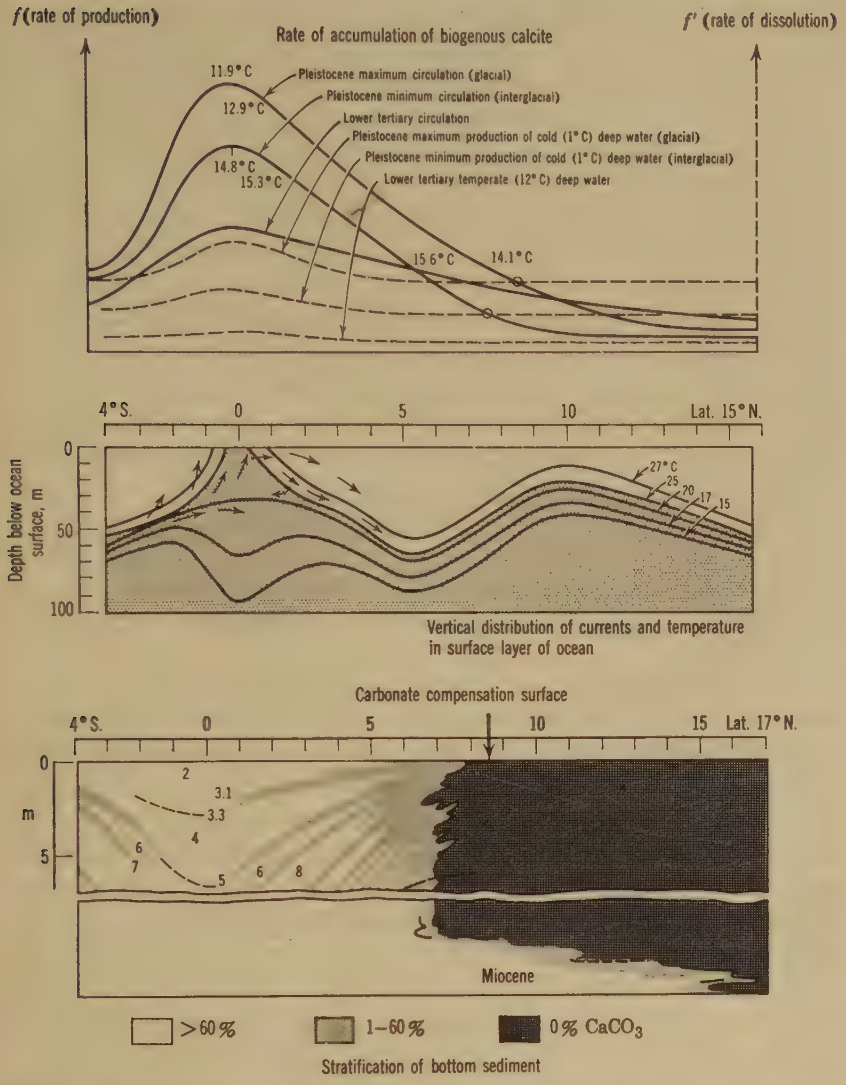

Fig. 8. Meridional profile at approximately longitude 130° W. in the Pacific Ocean, showing the distribution of properties in the surface layer of the ocean (middle graph), the stratification of the bottom sediment (lower graph), and interpretation of the sedimentary record in terms of rates of production, dissolution, and accumulation of calcium carbonate from planktonic organisms (upper graph).

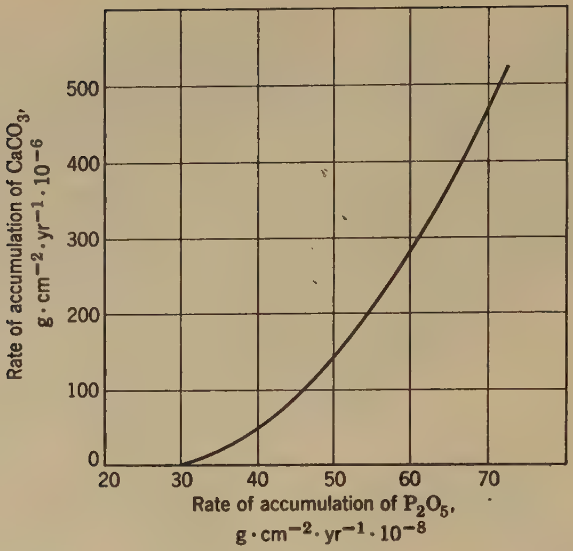

Fig. 9. Lower part of curve shown in figure 6, showing nonlinearity. This part of the distribution is based on approximately 300 samples (from Arrhenius, 1952, by permission).

below the zones of productivity. The characteristics of teeth, bone, and scale debris indicate that it is derived mostly from small species of bathypelagic fish.

In the range of accumulation rate of calcium carbonate below a few hundred $mg \cdot cm^{-2} \cdot millennium^{-1}$ the fraction of carbonate lost by dissolution on the ocean floor is large, and owing to the lower rate of dissolution of apatite as compared with calcite the sediments are left relatively richer in phosphate (fig. 9).

Cosmogenous Components

The accretion of solids from outer space occurs at such a low rate that cosmogenous objects of small size cannot be readily recognized in the rapidly accumulating terrestrial and epicontinental sediments. In slowly growing oceanic deposits, however, microscopic spherical droplets of nickel-iron are found, which are most probably of cosmic origin. The rate of accumulation of these objects appears to be of the order of $4 \cdot 10^{-8}$ $g \cdot cm^{-2} \cdot millennium^{-1}$ (Laevastu and Mellis, 1955), but the total rate of accretion of meteoritic dust may be higher. The nickel-iron droplets that have been found are approximately 15 to 230 microns in diameter. Smaller spherules could have formed a considerable proportion of the original distribution and might later have been decomposed by oxidation. An error of a factor of 2 in the estimate is possible from this effect. Further, cosmogenous silicates certainly accompany the nickel-iron dust reaching the earth, and it seems probable that the mass ratio of the two components is of the same order as the frequency ratio of observed falls of stone meteorites to those of iron meteorites, i.e. around 14. The total rate of accretion of unvaporized cosmogenous matter on the earth may thus be at least of the order of 10^{-6} $g \cdot cm^{-2} \cdot millennium^{-1}$, or 5000 tons over the surface of the earth per year.[1] A more accurate estimate of the accretion rate of unvaporized cosmogenous silicate dust and its variation with time might be obtained from a study of the distribution in pelagic clay sediments of the monoclinic magnesium-iron pyroxenes clinoenstatite-clinohypersthene, which occur in meteorites but are rare in tellurian igneous rocks.

Chronology of Ocean Sediments

The pelagic deposits provide a unique record of the general geological evolution of the earth during the Cenozoic era. Hence it is of interest to devise accurate methods for determination of the age of the strata that make up this system. The application of such methods further provides information on the rate of geological processes both in the past and at present.

The radiocarbon of biogenous calcite has been used to date late Glacial and Postglacial strata (Arrhenius, Kjellberg, and Libby, 1951; Arrhenius, 1952; Emiliani, 1955). These correspond to the top meter or less of the sediment, and the limitations of the method prevent dating of the deeper parts of the sequences. Attempts have been made to calibrate by radiocarbon some other property of the sediment believed to be time dependent, and to extrapolate the age in older strata from the distribution of this property. Depth in the core (Emiliani, 1955) has been chosen as such a property, on the basis of the fact that the thickness of individual strata is very uniform in certain profiles from the Atlantic Ocean and on the assumption that this indicates approximate constancy in time of the total rate of deposition, including biogenous, lithogenous, and hydrogenous solids.

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[1] This computation uses values for density, water content, and rate of deposition of the sediment based on more recent work and slightly different from those employed by Laevastu and Mellis.

In another case (Arrhenius, 1952) the variation in space of the rate of deposition of different components was investigated; it was found that in a topographically protected area distant from land in the east equatorial Pacific the rate of accumulation of titanium showed only little variability in space in spite of variations of the total rate of deposition by more than a factor of 10. It was also found that in those parts of this area where the biogenous contribution did not vary markedly with depth in the top few meters of sediment, i.e., with time throughout Upper Pleistocene, the titanium content remained nearly constant. These facts were taken to indicate that the rate of accumulation of titanium has remained constant within narrow limits during Upper Pleistocene over the area in question. A certain mass of titanium in a column of unit cross section would under these conditions approximately correspond to a definite length of time. This time span was determined by the radiocarbon age of the lower boundary of a column with a known titanium content.

Extrapolations based on this method, and on the one mentioned previously, give reasonable results, with agreement between the Atlantic and Pacific climatic records to an estimated age of about 100,000 years. For strata older than this, extrapolation in the Atlantic and the Pacific has given divergent results, leading to an estimate of about half a million years for the total length of the Pleistocene from the Atlantic record as compared with the order of a million years from the Pacific record. Efforts are therefore being made to determine the age of the Upper Pleistocene strata directly by a method involving the specific activity of ionium, described later.

Attempts have recently been made (Arnold, 1956; J. Merrill, M. Honda, and J. R. Arnold, unpublished; Goel et al., 1957; Peters, 1955, 1957) to use radioactive Be^{10} for age determination of marine sediments. This nuclide is formed in the upper atmosphere by the action of cosmic-ray particles on nitrogen and oxygen, and has a half-life of $2.7 \cdot 10^6$ years, which makes it quite suitable for work on Upper Pliocene and Pleistocene strata. One difficulty, however, is the short residence time (a few hundred years) of beryllium in sea water, preventing complete mixing through the oceans before precipitation takes place.

The refinement of the potassium-argon method has made it possible to measure sediments in the age range 10^7 to 10^8 years in cases where hydrogenous minerals occur with a satisfactory retentivity for argon (Wasserburg, Hayden, and Jensen, 1956). The hydrous mica glauconite has been used for this purpose. Further advantages may be offered by use of potassium-bearing hydrogenous apatite, which has a dense structure and thus possibly a high gas retentivity. Leakage of argon can be controlled by checking the amount of helium derived from uranium in the mineral.

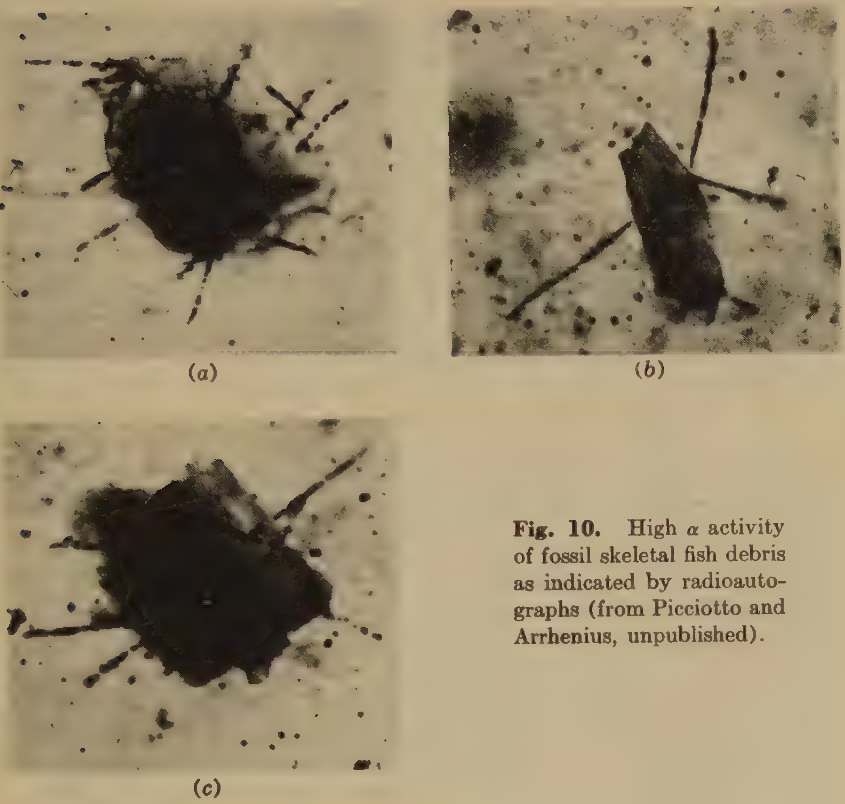
The recent development of a method for age determination by rhenium 187, decaying into osmium 187 with an estimated half-life of $6.2 \cdot 10^{10}$ years (Herr and Merz, 1958), is of potential usefulness for ocean sediments older than about $25 \cdot 10^6$ years, i.e. Lower and Middle Tertiary and older. The application of this method to marine sediments would require an investigation of the aqueous geochemistry of rhenium and osmium, as the accuracy in this case depends on a high specific concentration of the radiogenic osmium isotope.

The earliest attempts to develop an absolute method for age determination in pelagic sediments made use of the distribution of the members of the U^{238}-series elements. Pettersson in 1938 made the important discovery that the high radium content of young pelagic sediments is supported by the parent element Th^{230} (ionium), which is separated from its predecessor, uranium, by precipitation from solution in sea water. For technical reasons Pettersson and his co-workers (Pettersson, 1938, 1953; Kröll, 1955), as well as other workers in the field, chose to measure radon in equilibrium with radium, assuming that the radium in the sediment would be in equilibrium with ionium. It was soon found that in many sedimentary sequences radium is more irregularly distributed than would be expected from decay of regularly distributed ionium. In some Pacific sequences with strata containing much of the zeolite phillipsite, radium has been found to be concentrated in the phillipsite (Arrhenius and Goldberg, 1955). In the absence of indications of a corresponding concentration of ionium, it appears that, upon decay of ionium in the sediment, part of the radium formed goes into solution and diffuses through the sediment, and part is resorbed in minerals with high ion-exchange capacity. Another trap for migrating radium is provided by hydrogenous barite growing in the sediment, which thus becomes one of the most strongly α-active components of the sediment (Arrhenius, Bramlette, and Picciotto, 1957; Picciotto and Arrhenius, unpublished) (fig. 5). A considerable amount of the dissolved radium appears to be returned to the ocean by this diffusion process, and a corresponding increase of the radium content of sea water with increasing depth in the ocean has been demonstrated (Koczy, 1956).

It thus appears doubtful that the radium content of the sediment can in any case be interpreted in terms of geological age; also the lack of a specific activity in radium makes the results sensitive to variations in the rate of accumulation of the parent element and of other sedimentary components. A way out of this difficulty was indicated by Picciotto, who devised a method for the direct determination of the specific activity of ionium, using as a reference isotope Th^{232}. Goldberg and Koide (1958), who developed an α-spectrometric method for the simultaneous determination of ionium and thorium, carried out a number of determinations of the ratio Io/Th in sediment cores from the Pacific; they found a regular exponential decrease of the ratio with depth in the sediment, indicating that ionium is not redistributed after deposition. The ionium-thorium method thus appears promising as a tool for age determination in the Upper and Middle Pleistocene, and offers the special advantage of being independent of variations in the rate of deposition.

Uranium is also transferred, though at a very low rate, to the oxidized deep-sea sediments, giving rise to a small amount of supported ionium. Especially in strata with an age of several ionium half-lives, uranium-supported ionium becomes a significant fraction of the total ionium content, and the Io/Th ratio has to be duly corrected.

The assumptions on which the ionium-thorium method rests are that the two isotopes are in chemical equilibrium with each other in sea water, that the ratio Io/Th has remained constant over the period of time involved in a given water mass, and that the contribution of thorium and uranium in detrital minerals is negligible or can be checked. Similar assumptions are made when other radionuclides are employed for the chronology of ocean sediments. Hence, information on the path of the elements in question through the hydrosphere is a prerequisite for their use for geochronological purposes. Studies of the amounts and distribution of uranium and thorium in sea water have been made (Pettersson, 1953; Koczy et al., 1957; Sackett et al., 1958), but our knowledge of the relative distribution of ionium and thorium is still not conclusive. For the transfer of the thorium isotopes from the ocean to the sediment several mechanisms have been suggested, for example coprecipitation with ferric oxide hydrate (Pettersson, 1938) and absorption on clay minerals (Holland and Kulp, 1954). Studies of the distribution of these nuclides in the different solid phases of the sediment have demonstrated, however, that they are concentrated in the ferromanganese oxide–hydrate double-layer minerals (Goldberg and Picciotto, 1955)



(*a*) (*b*) (*c*)

Fig. 10. High α activity of fossil skeletal fish debris as indicated by radioautographs (from Picciotto and Arrhenius, unpublished).

and in the apatite crystallites of skeletal debris of fish (Arrhenius, Bramlette, and Picciotto, 1957; Picciotto and Arrhenius, unpublished) (fig. 10), whereas the clay minerals appear inactive. Living bathypelagic fish do not display the remarkable concentration of heavy metals typical of the skeletal debris in the sediment, and it thus appears that the transfer takes place during or after deposition and before burial of the fossil debris. The ionium in the ferromanganese minerals might be located in the ferric oxide hydrate part of the structure, which would support Pettersson's suggestion of ferric precipitates as scavengers of ionium from sea water. The concentration of ionium and thorium by identical processes in identical minerals provides a proof that the assumption of chemical equilibrium between species of thorium isotopes in sea water is justified, at least as far as the last phase of the transfer process is concerned.

Relative age determinations based on the evolutionary change of fossil-forming organisms have been made in calcareous and siliceous sediments, where fossil coccolithophorids, foraminifera, diatoms, and radiolarians have proved useful in distinguishing between the different Cenozoic epochs (Bramlette and Riedel, 1954; Riedel, 1957; Kolbe, 1955, 1957; Lohman, 1942; Phleger, Parker, and Peirson, 1953). The marked vertical variation in chemical composition of the Pleistocene strata, due to climatic change, provides a means for detailed correlation of stages and substages. Different strata, dated by absolute methods at one or a few localities, can thus be traced over large areas, both in the Atlantic (Bramlette and Bradley, 1942; Schott, 1935; Emiliani, 1955) and in the Pacific Ocean (Arrhenius, 1952).

The Geological Record of Sedimentation in the Ocean

Owing to difficulties in sampling sedimentary strata to greater depths than about 15 meters, most sediment cores from undisturbed parts of the ocean bottom so far studied contain only Recent and Plio-Pleistocene deposits. In numerous cases, however, short cores and dredge hauls from topographic highs have revealed that older, mostly Tertiary deposits outcrop or are covered unconformably by thin strata of younger sediments. Specimens older than Cretaceous have so far not been reported, and it is interesting to couple this fact with the small total thickness of sediments (200 to 300 meters) observed by seismic methods over large areas of the Pacific Ocean, possibly indicating widespread effusion of lava over the bottom in Cretaceous time (Revelle, Bramlette, Arrhenius, and Goldberg, 1955).

Oxygen-isotope data indicate that the temperature of the deep and bottom water during Early and Middle Tertiary was about 10° C higher than now, a value in accordance with the vaster expanse of calcareous sediments during these times due to lower rate of dissolution of calcium carbonate. The high ratio of hydrogenous to lithogenous minerals makes it probable that mechanical weathering on the continents was less extensive during Tertiary than at the present time. The cooling of the deep water body to the near-zero temperatures now prevailing is recorded at the Pliocene-Pleistocene transition (Emiliani, 1955), and strata with glacial drift in the middle latitudes indicate the penetration far south of icebergs during the glacial ages (Arrhenius, 1950). Simultaneous periods of cooling of the equatorial surface water are recorded by the oxygen-isotope ratio in the calcareous tests of planktonic foraminifera. The cooling is probably mainly due to invasion of cold water from higher latitudes in the Atlantic and to increased upwelling of deep water along the equatorial divergence in the Pacific.

The changes in time of biogenous deposition in the equatorial zone of high productivity in the Pacific are of particular interest, as there is a direct relation between the rate of organic productivity and the rate of upwelling of deep water, which, in turn, is determined by the intensity of the trade winds. The sedimentary stratification in this area thus provides a record of the low-latitude atmospheric circulation through Tertiary and Quaternary time. A condensed illustration of these conditions is presented in figure 8. The central diagram of this figure shows a meridional cross section through the surface layer of the ocean in the east equatorial Pacific at longitude 120–130° W., where the features of the vertical circulation are well developed, and where the regularity in lithogenous sedimentation makes possible a quantitative study of variations in time of the biogenous components.

The temperature distribution in this middle diagram is indicated by the isotherms for 15°, 17°, 20°, 25°, and 27° C. The cold, nutrient-rich intermediate water is marked by a dotted surface, and the vertical circulation pattern is shown by arrows. The Equatorial Countercurrent, running eastward, is limited by the South Equatorial Current at about 5° N., and by the North Equatorial Current at about latitude 10° N., both moving westward. Divergence of these wind drift currents produces upwelling along the equator. The rise of the intermediate water, which is rich in nutrient salts, into the surface layer, where most of the sunlight is absorbed, leads to a greatly increased production of algae, sustaining a corresponding production of other members of the food chain. At higher tropical latitudes the absence of a mechanism for enriching the euphotic layer keeps the productivity low. The resultant rate of production of skeletal calcium carbonate from coccolithophorids and foraminifera is illustrated in the upper diagram, where the full-line curve marked "Pleistocene minimum circulation (interglacial)" corresponds to present conditions. The scale of the abscissa axis is the same as in the middle graph. The inferred rate of dissolution of calcium carbonate before final burial of the fossils is indicated by the curve marked "Pleistocene minimum production of cold (1° C) deep water (interglacial)," which shows a flat maximum under the equatorial productivity maximum, due to the effect of carbon dioxide produced by the respiration of bottom-living animals feeding on the rain of organic detritus.

The resultant rate of accumulation of calcium carbonate corresponds to the ordinate difference between the two curves. At the intersection of these curves between latitude 7° and 9° N., carbonate accumulation accordingly drops to zero. Siliceous clays cover the bottom of the ocean north of the present loci of this intersection, the carbonate compensation line.

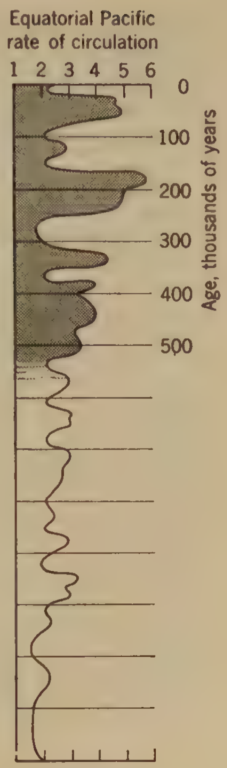
The temperature figures in the graph, referring to oxygen-isotope measurements (Emiliani and Edward, 1953; Emiliani, 1955) at latitude 0°, 2°, and 7° N., demonstrate qualitatively the increase in temperature away from the equator.

Before discussing the other curves in the upper graph, representing the conditions in the past, the lower diagram in figure 8 will be explained. This diagram is a generalized cross section through the bottom deposits along the same meridian as in the upper graphs. The ordinate has arbitrarily been chosen = 0 for the present sediment surface. The lower, detached half of the graph, showing the stratification of the Middle Tertiary sediments, is deficient in detail because of the paucity of observations. The shading indicates the carbonate concentration, which in a rough way reflects the rate of accumulation of carbonate.

The profile demonstrates the main features of the marked stratification of the calcareous deposits. Below the surface layer, which is characterized by relatively low carbonate concentrations, lies a stratum (2) high in carbonate, and coinciding in time with the last glaciation in higher latitudes. This stratum is preceded by another low-carbonate stratum (3) and a high-carbonate stratum (4), the last indicating extraordinarily high rates of accumulation of biogenous carbonate and silica. Altogether about nine major carbonate maxima occur in the Pleistocene part of the sequence. The underlying Pliocene sediments are characterized by less variability of the carbonate content with time. The Pliocene-Pleistocene transition, indicated by a rapid drop in bottom-water temperature (Emiliani, 1955) and by a marked change in the fossil assemblages of coccolithophorids (Bramlette, personal communication; Bramlette and Riedel, 1954), is shown as a dashed line crossing over the carbonate compensation surface near the break in the profile.

From measurements in stratum 4 the full-line curve marked "Pleistocene maximum circulation (glacial)" in the top diagram and the dashed curve marked "Pleistocene maximum production of cold (1° C) deep water (glacial)" have been constructed. The productivity appears to have been largely increased, especially in the equatorial divergence, and probably to some extent also the dissolution due to respiration of benthonic animals, although not enough to counterbalance the greatly

Fig. 11. Relative rate of low-latitude atmospheric circulation during the Pleistocene, estimated from the rate of accumulation of biogenous solids below the Equatorial Current system. The time scale is obtained by extrapolation based on the cumulative titanium content of the sediment, and should probably be considered as applicable only to the upper half million year part of the sequence (shaded). The Pliocene-Pleistocene boundary falls within the lowest two sections of the graph (from Arrhenius, 1952, by permission).



increased rate of deposition of calcareous skeletal remains. As a result the over-all rate of accumulation of calcium carbonate reaches a maximum during this time. The greatest increase occurs at the equator, where values of the order of 3 to 10 $g \cdot cm^{-2} \cdot millennium^{-1}$ of calcium carbonate are found. The paleotemperature data in the same graph indicate a steepening of the temperature gradient from the equator, which is taken as additional evidence for an increased rate of upwelling in the divergence as the cause of the increased productivity. The reason for this intensified vertical circulation occurring during the glacial ages is probably an increase in the tropical atmospheric circulation depending on a displacement toward the equator of the high-pressure centers now located between latitude 20° and 35°. Under these conditions the stratification of biogenous components in the equatorial Pacific provides a direct and undisturbed record of the climatic evolution of the earth during the last few million years. A reconstruction of the variations in trade-wind intensity on the basis of the sedimentary record is given in figure 11.

The examples cited above may serve to illustrate the advantages for quantitative geological studies offered by sediments from the water hemisphere. The properties of these sediments yield information on the physical, chemical, and biological reactions which regulate the composition of the ocean. The rates of the reactions have changed in the past, and these changes, recorded in the sedimentary strata, indicate world-wide modifications of the intensity of such processes as atmospheric circulation, volcanic activity, weathering, glaciation, and accretion of cosmic matter.

Owing to the low rates of accumulation, and the continuous, thorough mixing of the top stratum of the sediments by mud-eating animals, the oceanic record is smoothed, with a time factor estimated to vary between a few thousand and a few ten thousand years. This effect makes it difficult to resolve events of short duration, such as the post-glacial climatic oscillations. Most of the history recorded in pelagic sediments can be traced with a better time resolution in the sediments accumulated on and around the continents; local effects, however, frequently obscure or distort the record in these cases. The sedimentary record in protected areas of the ocean floor, far away from the continents, thus offers distinct advantages for a wide regional or global integration of geological processes and for their interpretation on a quantitative basis.

References

Arnold, J. R. 1956. Beryllium-10 produced by cosmic rays, *Science, 124,* 584–585.

Arrhenius, G. 1950. The Swedish deep sea expedition: The geological material and its treatment, *Geol. Fören. i Stockholm Förh., 72,* 185–191.

Arrhenius, G. 1952. Sediment cores from the East Pacific, *Rept. Swed. Deep Sea Expedition, 5,* Göteborg.

Arrhenius, G. 1954. Origin and accumulation of aluminosilicates in the ocean, *Tellus, 6,* 215–219.

Arrhenius, G., M. N. Bramlette, and E. Picciotto. 1957. The localization of radioactive and stable heavy nuclides in ocean sediments, *Nature, 180,* 85–86.

Arrhenius, G., and E. D. Goldberg. 1955. Distribution of radioactivity in pelagic clays, *Tellus, 7,* 226–231.

Arrhenius, G., G. Kjellberg, and W. F. Libby. 1951. Age determination of Pacific chalk ooze by radiocarbon and titanium content, *Tellus, 3,* 222–229.

Bramlette, M. N., and W. H. Bradley. 1942. Geology and biology of North Atlantic deep sea cores between Newfoundland and Ireland, I, Lithology and geologic interpretations, *U. S. Geol. Survey Profess. Paper 196a.*

Bramlette, M. N., and W. Riedel. 1954. Stratigraphic value of discoasters and some other microfossils related to recent coccolithophores, *J. Paleontol., 28,* 385–403.

Buser, W., and A. Grütter. 1956. Über die Natur der Manganknollen, *Schweiz. mineral. petrog. Mitt., 36,* 49–62.

Correns, C. W. 1953. Der Anteil des Staubes an der Bildung der Sedimentgesteine, *Z. Ver. deut. Ing., 95,* 293–296.

Correns, C. W., and W. von Engelhardt. 1938. Neue Untersuchungen über die Verwitterung des Kalifeldspates, *Chem. Erde, 12,* 1–22.

Dietz, R. 1955. Manganese deposits on the northeast Pacific sea floor, *Calif. J. Mines Geol., 51,* 209–220.

Emiliani, C. 1955. Pleistocene temperatures, *J. Geol., 63,* 538–578.

Emiliani, C., and G. Edward. 1953. Tertiary ocean bottom temperatures, *Nature, 171,* 887–889.

Goel, P. S., D. P. Kharkar, D. Lal, N. Narsappaya, B. Peters, and V. Yatirajam. 1957. The beryllium-10 concentration in deep sea sediments, *Deep Sea Research, 4,* 202–210.

Goldberg, E. D., and G. Arrhenius. 1958. Chemistry of Pacific pelagic sediments, *Geochim. et Cosmochim. Acta, 13,* 153–212.

Goldberg, E. D., and M. Koide. 1958. Ionium-thorium chronology in deep sea sediments of the Pacific, *Science, 128,* 1003.

Goldberg, E. D., and E. Picciotto. 1955. Thorium determinations in manganese nodules, *Science, 121,* 613–614.

Goldberg, E. D., and R. W. Rex. 1958. Quartz contents of pelagic sediments of the Pacific Ocean, *Tellus, 10,* 153–159.

Herr, W., and E. Merz. 1958. Zur Bestimmung der Halbwertszeit des ^{187}Re, Weitere Datierungen nach der Re/Os Methode, *Z. Naturforsch., 13a,* 231–233.

Holland, H. D., and J. L. Kulp. 1954. The transport and deposition of uranium, ionium, and radium in rivers, oceans, and ocean sediments, *Geochim. et Cosmochim. Acta, 5,* 197–213.

Koczy, F. 1956. Vertical eddy diffusion in deep water, *Nature, 178,* 585.

Koczy, F., E. Picciotto, G. Poulaert, and S. Wilgain. 1957. Mesure des isotopes du thorium dans l'eau de mer, *Geochim. et Cosmochim. Acta, 11,* 103–129.

Kolbe, R. W. 1955. Diatoms from equatorial Atlantic cores, *Rept. Swed. Deep Sea Expedition, 7,* 3.

Kolbe, R. W. 1957. Diatoms from equatorial Indian Ocean cores, *Rept. Swed. Deep Sea Expedition, 9,* 1.

Kröll, V. 1955. The distribution of radium in deep-sea cores, *Rept. Swed. Deep Sea Expedition, 10,* 1, Göteborg.

Kuenen, Ph. H., and C. I. Migliorini. 1950. Turbidity currents as a cause of graded bedding, *J. Geol., 58,* 91–127.

Laevastu, T., and O. Mellis. 1955. Extraterrestrial material in deep sea deposits, *Trans. Am. Geophys. Union, 36,* 385–389.

Lohman, K. 1942. Geology and biology of North Atlantic deep sea cores between Newfoundland and Ireland, 3, Diatomaceae, *U. S. Geol. Survey Profess. Paper 196b.*

McDonald, W. F. 1938. Atlas of climatic charts of the oceans, *U. S. Dept. Agr., Weather Bureau, no. 1247.*

Menard, H. W. 1956. Archipelagic aprons, *Bull. Am. Assoc. Petrol. Geologists, 40,* 2195–2210.

Menard, H. W. 1958. La topographie et la géologie des profondeurs océaniques, *Coll. Intern. Centre natl. recherche sci., 83.*

Norin, E. 1958. The sediments of the central Tyrrhenian Sea, *Rept. Swed. Deep Sea Expedition, 3,* 1.

Peters, B. 1955. Radioactive beryllium in the atmosphere and on the earth, *Proc. Indian Acad. Sci., 41,* 67–71.

Peters, B. 1957. Über die Anwendbarkeit der Be-10 Methode für Messung kosmischer Strahlungsintensität und der Ablagerungsgeschwindigkeit von Tiefseesedimenten vor einigen millionen Jahren, *Z. Physik, 148,* 93.

Pettersson, H. 1938. *Mitt. Inst. Radiumforschung, 400a.*

Pettersson, H. 1953. Radium and the deep sea, *Am. Scientist, 41,* 245–255.

Phleger, F., F. Parker, and J. Peirson. 1953. North Atlantic Foraminifera, *Rept. Swed. Deep Sea Expedition, 7,* 1.

Radczewski, O. E. 1939. Eolian deposits in marine sediments, *Recent Marine Sediment Symposium* (P. D. Trask, ed.), pp. 496–502, American Association of Petroleum Geologists, Tulsa, Oklahoma.

Revelle, R., M. N. Bramlette, G. Arrhenius, and E. D. Goldberg. 1955. Pelagic sediments of the Pacific, *Geol. Soc. Am., Spec. Paper 62,* 221–236.

Riedel, W. 1957. Radiolaria: A preliminary stratigraphy, *Rept. Swed. Deep Sea Expedition, 6,* 3.

Sackett, W., H. Potratz, and E. D. Goldberg. 1958. Thorium content of ocean water, *Science, 128,* 204–205.

Schott, W. 1935. Die Foraminiferen in dem äkvatorialen Teil des atlantischen Ozeans, *Wiss. Ergeb. deut. atl. Exped. Meteor, 1925–1927, 3,* 3.

Vinogradov, A. P., and A. B. Ronov. 1956. Composition of sedimentary rocks of the Russian platform in relation to the history of their tectonic movements, *Geokhimiya, 6,* 3–24 (in Russian).

Wasserburg, G., R. Hayden, and K. Jensen. 1956. A^{40}-K^{40} dating of igneous rocks and sediments, *Geochim. et Cosmochim. Acta, 10,* 153–165.

Weaver, C. E. 1958. Geologic interpretation of argillaceous sediments, *Bull. Am. Assoc. Petrol. Geologists, 42,* 254–271.